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SALTWATER CONTAMINATION OF A CUTOVER BOG: SOLUTE TRANSPORT MECHANISMS AND RESTORATION IMPLICATIONS, POKESUDIE ISLAND, NEW BRUNSWICK

Sarah M. Mouneimne

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POKESUDIE ISLAND, NEW BRUNSWICK

University of Waterloo

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A Senior Honours Thesis Submitted in Partial Fulfillment of the Degree of Bachelor of Environmental Studies (Honours Geography)

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June 2004

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ABSTRACT

There is relatively little research on the mechanisms governing solute transport and contamination in cutover (harvested) bogs, yet such research has important implications for coastal harvested peat bogs. Such sites are susceptible to saltwater contamination from both storms and from saltwater intrusion. The cutover bog on Pokesudie Island (47.8°N, 64.78°W; max. elevation of 4 m a.s.l.) was exposed to a 1.2 to 2.0 m storm surge on 21 January 2000. This storm surge resulted in contamination of the peat and a subsequent closure of the site to commercial harvesting. The peat depth ranges from approximately 0.5 to 4.0 m.

Monitoring of hydrological conditions at Pokesudie occurred from 6 May to 14 August 2003. The objective of this research was to identify the vertical and horizontal movements of water and solutes within the peat profile, both at the surface and at depths. In addition, the vertical distribution of salt was determined using four peat cores taken to depths of 125 to 205 cm. Salt contamination was monitored using electrical conductivity, salinity and chloride concentrations.

Both specific yield and bulk density do not vary with depth, and have average values of 0.23 and 0.09 g cm^{3} respectively. There was a downward flow of water in the natural zone, with horizontal flow directed toward the ocean. In the harvested zone, the frost table receded by 0.8 cm d^{1} until 17 July, after which it was patchy. However, many piezometers and wells were frozen until late July or early August, hampering some monitoring efforts. There was a strong relationship observed between salinity and electrical conductivity (r^2 = 0.9982) and between salinity and chloride concentrations (r^2 = 0.9894). The highest recorded surface salinity value was 17% at station no. 2 on Julian day 196, during an extended dry period. The peak salinity in the vertical peat profile was 8.1% and occurred at 75 cm from the peat surface.

It was observed that the source of solutes was the surface, consistent with inundation of saltwater during the storm surge. Spatially, salinity is concentrated in the lower-lying elevations, which were more heavily inundated and which undergo less leaching and greater concentration of surface solutes due to high evaporation rates. At the peat surface, there is also temporal variability of solute concentrations, with a concentration of solutes during periods of evaporation, and a leaching of solutes during precipitation events.

This preliminary research has identified vertical and horizontal flows of water and solutes, although it has also raised further questions that should be investigated. Primarily, research should determine the relative roles of cryogenic processes, snowmelt, advection and diffusion in the transport of solutes. There also needs to be an evaluation of the permeability of the sand substrate, as well as a determination of potential flow across the peat/sand boundary.

RÉSUMÉ

Il y a relativement peu de travaux de recherche sur les mécanismes qui régissent le transport de soluté et la contamination des tourbières commerciales, et pourtant ce genre de recherche a des incidences importantes sur les tourbières commerciales en milieu côtier. Ces environnements sont sujets à la contamination par l'eau de mer qui provient des tempêtes et de l'infiltration de l'eau salée. Le 21 janvier 2000, la tourbière en exploitation de l'île Pokesudie (47° 8' de latitude N., 64° 78' de longitude O.; élévation maximale de 4 m au-dessus du niveau de la mer) a subi une onde de tempête de 1,2 à 2,0 m. Cette onde de tempête a entraîné la contamination de la tourbe et a provoqué par la suite la cessation des activités d'extraction commerciale de la tourbe. La profondeur de la tourbe y varie en règle générale entre 0,5 et 4,0 m.

Un examen des paramètres hydrologiques de la tourbière de Pokesudie a eu lieu entre le 6 mai et le 14 août 2003. Ce projet de recherche visait à définir les mouvements verticaux et horizontaux de l'eau et des solutés dans le profil de la tourbe, en surface et en profondeur. De plus, la répartition verticale du sel a été établie au moyen de quatre carottes de tourbe recueillies à des profondeurs variant entre 125 et 205 cm. La contamination au sel a été examinée par des mesures de la conductivité électrique, de la salinité et des concentrations de chlorure.

La capacité de libre écoulement et la densité apparente ne varient pas selon la profondeur, et les valeurs moyennes observées s'établissement respectivement à 0,23 et à 0,09 g/cm^3. Dans la zone à l'état naturel, il y avait un écoulement vers le substratum, accompagné d'un écoulement horizontal en direction de l'océan. Dans la zone exploitée, il y a eu un rétrécissement de l'étendue de la table de gel-dégel de 0,8 cm/j^1 jusqu'au 17 juillet, après quoi la table est devenue éparse. Par contre, un grand nombre de piézomètres et de puits d'observation sont demeurés gelés jusqu'à la fin de juillet ou au début d'août, ce qui a quelque peu nui aux efforts de surveillance. On a relevé une forte corrélation entre la salinité et la conductivité électrique (r^2 = 0,9982), de même qu'entre la salinité et les concentrations de chlorure (r^2 = 0,9894). La plus forte salinité en surface (17 %) a été enregistrée à la station n° 2 le jour julien 196, pendant une période de sécheresse soutenue. La salinité la plus élevée affichée dans le profil de tourbe vertical a été de 8,1 % et a été observée à 75 cm de la surface de la tourbe.

Les solutés provenaient de la surface, ce qui semblait correspondre à l'inondation d'eau salée provoquée par l'onde de tempête. Au plan spatial, la salinité était principalement confinée dans les dépressions, lesquelles ont été davantage inondées, ces secteurs ayant par ailleurs

subi une lixiviation moindre et affiché une plus grande concentration de solutés de surface en raison des taux d'évaporation élevés. À la surface de la tourbe, on a aussi noté une variabilité temporelle des concentrations de soluté, en particulier en période d'évaporation, et elle était accompagnée d'une lixiviation des solutés pendant des précipitations données.

Cette recherche préliminaire a permis d'établir les écoulements verticaux et horizontaux de l'eau et des solutés, mais ces observations ont par ailleurs soulevé d'autres questions qui mériteraient une étude plus approfondie. Pour l'essentiel, les futurs travaux de recherche devraient chercher à définir les rôles respectifs des procédés cryogéniques, de la fonte des neiges, de l'advection et de la diffusion dans le transport des solutés. Il faudrait aussi évaluer la perméabilité du substrat sablonneux et établir la possibilité d'un écoulement à travers la zone de contact entre la tourbe et le sable.

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To everyone, this thesis is as much yours as it is mine. Merci mille fois!

1.0 INTRODUCTION

1.1 Background

1.1.1 Hydrology of Undisturbed and Drained Bogs

Bogs, by definition, receive only atmospheric water inputs (Ingram, 1983). As a result, the water held within the bog is poor in nutrients. These low nutrient conditions, along with acidic water conditions (pH < 4.2), can be tolerated only by a limited number of species. The dominant vegetation within a bog is *Sphagnum*, which forms the primary component of peat (Clymo, 1983). Peat is an organic soil that accumulates as the *Sphagnum* plants die and partially decompose. The anaerobic condition caused by the waterlogged soil slows decomposition, and allows for the accumulation of organic matter.

Undisturbed bogs are diplotelmic (two-layered) systems. The upper 30 to 50 cm of peat constitutes the acrotelm, the layer of living and poorly decomposed plant material (Ingram 1978). As the water table fluctuates, it exposes different portions of the acrotelm to aerobic conditions which promote more rapid decomposition. There is a general trend of an increasing state of decomposition with depth, corresponding to the older peat present at depths. Peat formed within the acrotelm gradually becomes part of the catotelm (the underlying layer) as it decomposes (Wheeler and Shaw, 1995).

The level of decomposition affects the hydrological characteristics of the acrotelm. Bulk density increases significantly with depth (Hoag and Price, 1997), while porosity and average pore size decreases with depth (Reeve *et al.*, 2000; Hoag and Price, 1997; Wheeler and Shaw, 1995; Ingram, 1983). Consequently, hydraulic conductivity decreases with depth by up to four orders of magnitude from the top to the bottom of the acrotelm (Price *et al.*, 2003). Due to its relatively high hydraulic conductivity, the acrotelm is a zone of rapid vertical and horizontal water movement (Reeve *et al.*, 2000; Ingram, 1983).

The acrotelm has a high water storage capacity as a result of its high specific yield, which decreases with depth from approximately 0.5 to 0.1 (Price *et al.*, 2003). This high specific yield allows the acrotelm to minimize water table fluctuations. The catotelm underlies the acrotelm layer, and comprises the majority of the peat volume within the bog. It is a layer of highly decomposed and non-living plants and materials. The continual saturation of this layer causes an anaerobic condition that slows the rate of decomposition of the catotelm peat (Clymo, 1984). There is little variation in hydraulic properties with depth, although the properties are significantly different from that of the acrotelm (Ingram, 1983). The catotelm has a higher bulk density, lower specific yield and smaller pores than the acrotelm (Price *et al.*, 2003; Hoag and Price, 1995; Wheeler and Shaw, 1995; Ingram, 1983). The hydraulic conductivity of the catotelm is three to six orders of magnitude lower than that of the acrotelm (Reeve *et al.*, 2000; Boelter, 1995; Hoag and Price, 1995). This significantly lower conductivity has implications for both water and solute transport, as will be discussed in section 1.1.2.

This two layer (diplotelmic) soil system is an essential component that maintains the hydrological balance in an undisturbed bog (see Price *et al.*, 2003; Wheeler and Shaw, 1995). During periods of excess precipitation, the bog can readily discharge excess water through the permeable acrotelm, with only a relatively minimal drop in water table elevation. During extended dry periods, the water table will drop into less permeable layers of peat, thus slowing runoff and minimizing water loss. Both layers contribute to the regulation of a relatively stable water table elevation, and minimize substantial water table fluctuations. These conditions allow for the development of bog plants, and for the continued accumulation of peat within the system.

Hydrological Effects of Drainage

Large-scale mechanical harvesting operations require removal of the acrotelm and partial drainage of the catotelm layer to facilitate harvesting operations. The presence of the acrotelm is a critical component to the normal development and functions of a raised bog (Wheeler and Shaw, 1995). Removal of the acrotelm exposes the underlying catotelm layer, while drainage results in a drop in water table elevation below the catotelm surface. These two activities cause a change in the water storage characteristics of the bog (see Schlotzhauer and Price, 1999; Wheeler and Shaw, 1995; Heathwaite, 1994).

Removal of the acrotelm reduces the overall specific yield of the bog. As a result, it has been found that the specific yield of cutover bogs declined from approximately 0.2 to 0.05 following acrotelm removal and drainage installation (Price *et al.*, 2003; Van Seters and Price, 2002; Price, 1997, Price, 1996). This lower specific yield causes an increase in the amplitude of water table fluctuations. The bog is no longer able to regulate the water table during periods of excess precipitation or extended dryness. A low specific yield means that a small loss or addition of water to the system will cause an exaggerated water table decline or rise (Price *et al.*, 2003). Van Seters and Price (2003) found that water table fluctuations in a cutover area were 67% greater than in a nearby undisturbed bog.

Bulk density also increases after drainage and acrotelm removal, due to volume change and removal of the low bulk density acrotelm. Van Seters and Price (2003) found that bulk density increased from 0.07 to 0.13 g cm^{-3}, while Silins and Rothwell (1988) noted that bulk density in a cutover bog was 63% higher than in the nearby undisturbed bog (after seven years of drainage). The higher bulk density is also coupled with smaller pore sizes. As a result, the saturated hydraulic conductivity of cutover peat is much lower than that of an undisturbed peatland (Van Seters and Price, 2002; Wheeler and Shaw, 1995).

The installation of drainage ditches causes uneven drawdown of the water table. There is greater water table drawdown near the ditches than towards the centre of the balks

(Rothwell *et al.*, 1996). The distance of this drawdown effect varies based on the specific properties of the peat, the ditch spacing and the ditch depth. Boelter (1972) found drawdown within 5 m of the ditch in highly decomposed peat, although this drawdown influence was extended to within 50 m in less decomposed peat. Similarly, Prévost *et al.* (1997) found water table drawdown occurred within 15 m of the ditches, with the most significant drawdown within 5 m.

Volume Change Theory

Peat is a highly deformable matrix that can accommodate water storage changes by expansion and compaction of the peat matrix (Schlotzhauer and Price, 1999). In cutover and drained bogs, the low water table and resulting high overburden pressure cause volume change within the peat matrix (Price *et al.*, 2003; Price, 2003; Van Seters and Price, 2002; Price and Schlotzhauer, 1999). This volume change takes three primary forms: shrinkage and oxidation occur above the water table, while compression occurs below (Price *et al.*, 2003). Oxidation and compression cause an irreversible lowering of the peat surface over the long term (Van Seters and Price, 2002; Price and Schlotzhauer, 1999), while shrinkage is partially reversible upon rewetting of the peat (Van Seters and Price, 2002; Price and Schlotzhauer, 1999).

Compression is caused by the loss of buoyancy of the peat fibres upon drainage, and the consequent increase in stress upon peat fibres below the water table (Ilniki, 2003; Price, 2003; Kennedy and Price, in press). This increased stress causes the peat below the water table to compress, resulting in a more compact matrix that is able to support the overlying weight. During compression, the volume change is equivalent to the volume of water expelled from storage (Price, 2003; Price and Schlotzhauer, 1999).

Shrinkage is the contraction of the peat soil due to the development of negative pore water pressures between peat fibres (Kennedy and Price, in press). The negative pore

pressures can cause collapse of some pores within the soil matrix. More decomposed peat undergoes greater shrinkage due to the higher degree of small pores in which this negative pore water pressure can occur (Ilnicki and Zeitz, 2003). Unlike compression, the loss of soil volume may not equal the loss of soil moisture since the matrix is partially air-filled (Schlotzhauer and Price, 1999).

Compression and shrinkage can occur over the long-term following drainage (Silins and Rothwell, 1998), or over the short-term in response to the seasonal water deficit (Price 2003). Oxidation, however, affects soil structure only over the longer term (Clymo, 1984), and is irreversible.

Each of these three processes contributes to the overall subsidence of the peat surface of a drained cutover bog. Compression results in a much larger total volume change than shrinkage since there is a greater volume of peat below the water table in which compression occurs. Price and Schlotzhauer (1999) found that shrinkage resulted in subsidence of the peat surface by 3.6 cm, while compression resulted in approximately 6 cm of subsidence. In another study, Schothorst (1997) reported that 10% of the volume change could be attributed to shrinkage, 35% to compression, and 55% to oxidation (after six years of drainage). While shrinkage and compression will occur primarily within the first few years after drainage, oxidation is an ongoing process which continues to lower the elevation of the peat surface.

The nature of the total volume change and surface elevation change depends upon the compressibility of the peat (Price and Schlotzhauer, 1999; Hobbs, 1986; also see Cagampan, 2004). Not all peat is composed of the same materials, with the same level of decomposition. Peat that is more highly decomposed will be less compressible than that which is composed primarily of less decomposed *Sphagnum* fibres.

Volume change and compression of the peat matrix will alter the water storage functions within the peatland (Price, 1996). Compression causes an increase in bulk

density, and water is expelled from storage (Schlotzhauer and Price, 1999; Price, 2003). Compression and shrinkage cause a shift in pore size distribution since the larger pores are the first to collapse. The greater proportion of smaller pores causes a lower hydraulic conductivity and a decreased specific yield (Price *et al.*, 2003; Price, 2003; Silins and Rothwell, 1998; Price, 1996). The lower hydraulic conductivity will reduce the rate at which water and solutes will travel through the peat matrix, reducing the vertical and lateral water movement (Price *et al.*, 2003).

1.1.2 Solute and Water Movement through Peat Soils

Vertical and Horizontal Flows of Water

Vertical and horizontal flow is caused by hydraulic gradients within a peat soil. Flow is governed by total hydraulic head, which is a function of both pressure and gravity. The magnitude and direction of flow can also be influenced by certain peat characteristics. Hydraulic conductivity will affect the rate at which water moves through a soil. Changes in hydraulic conductivity (frequently due to subsidence) will alter this rate of flow, and may cause a change in flow direction. Areas with a higher hydraulic conductivity will be natural conduits for water flow (Helling and Gish, 1991). Similarly, the size of pores and their interconnectivity will affect the direction and rate at which water moves and drains from a soil. In addition, changes to specific yield will cause a change in the ability of the bog to store water, and will alter the ability of the system to minimize water table fluctuations.

Flow theories have been developed to explain the rate and direction of flow within a soil matrix. Both preferential flow and fingering identify spatial variations in water flow through a soil matrix. Peat has been found to be a dual porosity matrix, which affects flow through various pore sizes and structures. In addition, the shallow flow and vertical flow models identify different theories that relate to the vertical and horizontal flow of water through peatlands.

Flow occurs at two scales: through small and large pores (Luxmoore, 1991). Within the smaller pores, water and its constituents can interact chemically with the soil matrix; these pores will only drain once they have become saturated. Alternatively, flow can occur through larger pores, which can simply become physical conduits for water. There is no chemical interaction with the surrounding soil matrix. Such flow through relatively larger pores is termed preferential flow.

Preferential flow is the process whereby water moves by preferred pathways through a porous media (Helling and Gish, 1991). As a result, water flows preferentially through a portion of the soil matrix. Such flow can occur through cracks, root holes and animal holes, as well as along a physical conduit such as a root. Although large pores are generally called 'macropores', there is no universally accepted definition for this term. As a result, preferential flow only refers to flow through relatively large pores (Helling and Gish, 1991). Preferential flow results in the infiltration of water to greater depths than would be expected based on classical Darcian flow theory (Weinhold and Gish, 1991). It is affected by porosity and by changes in pore size distribution caused by subsidence (Helling and Gish, 1991).

Although preferential flow affects the spatially variable distribution of soil moisture after rainfall events, some soils demonstrate considerably different patterns of preferential flow that cannot be explained by pore sizes alone. Such flow is termed fingering, and is a type of preferential flow that is caused by an uneven wetting front (Helling and Gish, 1991). Researchers have used both dyes and tracers to track both fingering and preferential flow through soils. It has been found that abrupt changes in hydraulic conductivity, compression of air in advance of a wetting front, and the redistribution of water upon slowing of the flow rate all contribute to fingering (Helling and Gish, 1991). This flow theory identifies the physical soil properties, in addition to porosity, that can affect the spatial variability of flow.

Like all soils, peat contains pores of different sizes, although it is unlike other soils in that some of its pores were created from plant cells, roots or wood pieces. As a result, peat

is a dual porosity matrix, in that it has both active (open) pores and inactive (fully or partially closed) pores (Hoag and Price 1997). The active pores are inter-connected and actively transmit water. The active transport zone is comprised of four main types of pores (listed in order of decreasing ability to transport water): large, multiply-connected pores; simply connected slit pores; pores in wood and root structures, that are more or less intact; and pores in cell remains, with cell walls that are more or less intact (Loxham, 1980). In addition to the active pores, peat contains a considerable dead zone of inactive pores, which is comprised of both closed ended pores and completely isolated pores (Loxham, 1980). The proportion of closed pores increases with depth, since highly decomposed peat has a larger proportion of closed pores than less decomposed peat (Hoag and Price, 1997).

With regards to the vertical and horizontal flow of water at the larger scale of the peatland, there are two current models that are relevant: the shallow flow and groundwater flow theories. The shallow flow model is predicated upon an assumption that the more decomposed peat (which typically occurs at depths) is relatively impermeable due to a low hydraulic conductivity (Reeve *et al.*, 2000; Devito *et al.*, 1997; Ingram, 1983). It is assumed that this relatively impermeable deep peat isolates the acrotelm and the upper layers of the catotelm from the mineral soil below. As a result, it is postulated that water flow occurs only in the acrotelm and the upper catotelm, and that there is no flow interaction with the mineral soil underlying the peat substrate. The main direction of flow in this model is horizontal.

Conversely, the groundwater flow model examines the possibility that there is vertical flow within a peatland. It has been found that vertical flow is not necessarily limited by the low conductivity of the humified peat in the deeper catotelm layer (Reeve *et al.*, 2000; Price and Woo, 1988). Instead, vertical groundwater flow across the peat/mineral soil boundary is controlled by the permeability of the mineral soil underlying the peat (Reeve *et al.*, 2000). Where the mineral layer is permeable, there can be vertical flow. However, flow will be dominantly horizontal where the mineral layer is relatively impermeable.

The groundwater flow model also explains vertical flow near the peat surface. During wet periods, there has been found to be a recharge of groundwater away from the peat surface (Fraser *et al.*, 2001; Devito *et al.*, 1997). This recharge is caused by a higher hydraulic head at the peat surface and a lower hydraulic head at depths, which results in a net downward flow of water. Conversely, during dry periods there is a net discharge of water towards the peat surface. Evaporation and surface drying causes a lower hydraulic gradient at the peat surface, which results in an upward flow of water (Fraser *et al.*, 2001; Devito *et al.*, 1997). This process serves to maintain the saturation of peat during a dry period (Devito *et al.*, 1997).

Evapotranspiration (ET) becomes a dominant force in driving the upward flow of water when the rate of ET exceeds precipitation (Nuttle, 1988). However, this water loss does not necessarily imply a resultant drop in water table elevation, since a drying of the peat above the water table may negate the need for a water table response (Schlotzhauer and Price, 1999). ET also affects the rate of drainage through ditches, where higher ET rates reduce the rate of drainage during the summer months (Nuttle, 1988). During the winter, the reduced rates of ET result in greater drainage due to a higher hydraulic head (Nuttle, 1988). With regards to the difference between the ET of cutover and undisturbed bogs, different studies have documented either similar rates of ET (Van Seters and Price, 2001; Price, 1996) or reduced rates of ET on cutover bog sites (Price *et al.*, 2003; Heathwaite, 1994).

Flow is also affected by the presence of ground frost, which persists longer into the summer at cutover sites than at undisturbed natural bogs (Price, 1996). Cutover bogs freeze much deeper than undisturbed bogs because there is no vegetation to provide cover and to trap snow, since both vegetation and snow act as insulators and prevent ground frost (Price *et al.*, 2003). Cutover sites maintain much lower soil temperatures during the fall,

winter and spring months than natural sites, while they also maintain much higher summer soil temperatures than natural sites (Prévost *et al.*, 1997).

Vertical and Horizontal Flows of Solutes

The movement of solutes is related to the flow of water. The structure of peat means that solute transport will occur differently in peat than in other soil types, such as sand or clay. The main transport mechanisms include advection, diffusion and dispersion, as well as flow caused by density gradients.

Advection is the process whereby dissolved solutes are transported along with the bulk movement of water (Hoag and Price, 1997; Fetter, 1994; Freeze and Cherry, 1979). Advection by flowing water is controlled by three main mechanisms (Price and Woo, 1988; Lindberg and Harris, 1973): changes in hydraulic pressure caused by precipitation or evapotranspiration, horizontal groundwater flow along a hydraulic gradient, and changes in groundwater pressure caused by tidal flows. Alongside advection, preferential flow facilitates the movement of salts within the peat, and can help explain spatial variability in solute distribution (Wilcox, 1986).

Diffusion is a much less influential transport mechanism than advection, which is the primary transport mechanism for solutes (Wilcox, 1986). Diffusion is the process by which solutes dissolved in water move from areas of higher concentration to areas of lower concentration (Fetter, 1994; Freeze and Cherry, 1979). Diffusion is generally a slow process, and it continues until the concentration gradient is eliminated (Freeze and Cherry, 1979). Diffusion does not proceed as fast in porous media as in water, because solutes must follow indirect routes through pores and around mineral grains (Fetter, 1994). As a result, traditional diffusion models cannot be used to predict the rate of diffusion within a soil, because diffusion is highly dependent upon the structure, size and connectivity of the pore

network. In addition, diffusion can occur with or without the flow of water, so long as the soil is partially wetted (Fetter, 1994).

Diffusion flow along concentration gradients will also be affected by the hydraulic conductivity of the peat (Hoag and Price, 1997). Advective flow will occur primarily in areas of high hydraulic conductivity. This flow will create a concentration gradient of solutes in the area of high hydraulic conductivity (high concentration) to the low hydraulic conductivity areas (low concentration), thereby causing diffusion of solutes into areas of lower conductivity.

As solute-rich water moves through the peat matrix, it interacts with freshwater which causes dispersion of the solutes. Dispersion is the process whereby solute-rich water is diluted through mixture with freshwater (Fetter, 1994). Spatial heterogeneity in hydraulic conductivity is expected to enhance mechanical dispersion during the advection process (Reeve *et al.*, 2001). Mechanical dispersion is caused by differences in water flow velocities which result from spatial heterogeneities in the flow path (Reeve *et al.*, 2001; Hoag and Price, 1995). At slower water velocities, solute-rich water will interact with freshwater more than if the water were flowing at a higher velocity.

Solute-rich water is denser than freshwater; this higher density results in a vertical layering of water within an aquifer which contains both dense solute-rich water and less dense freshwater. The movement of higher density water due to gravitational effects is called density dependent flow, and causes the downward movement of solutes over time (Hoag and Price, 1995).

Despite all mechanisms for transporting solutes through the peat matrix, the movement of solutes is retarded by the closed pores of the dual porosity matrix. Most solute transport in the dual porosity peat medium occurs through the larger, active pores (Ours *et al.*, 1997; Hoag and Price, 1995). However, it has been found that solutes do not travel as fast as would be predicted based on calculated rates of advection (see Hoag and Price,

1995; Fetter, 1994). As a result, it is postulated that the closed pores retard the transport of solutes by acting as sinks (Hoag and Price, 1997; Ours *et al.*, 1997; Hoag and Price, 1995). The concentration gradient between the closed and active pores results in a variable flow of solutes between these two pores; the direction of flow is governed by the direction of the concentration gradient (Hoag and Price, 1997). There is a greater retardation of solutes at depths, since there is a greater proportion of closed pores in which solutes can be temporarily trapped (Hoag and Price, 1997).

There are also variable rates of solute movement through the acrotelm and catotelm layers. Hoag and Price (1995) found a rapid movement of solutes through the permeable acrotelm, and no infiltration of solutes into the catotelm layer within the first year of solute contamination. The following year, the solutes had moved only 0.15 m into the catotelm, likely due to the processes of diffusion and density dependent flow (Hoag and Price, 1995). Wilcox (1986) recorded similar findings for a bog contaminated by road salts, where salinity increased with depth to the acrotelm-catotelm boundary, then decreased with depth in the catotelm layer.

With regards to the vertical and horizontal transport of solutes on a larger scale, the two models of water flow (shallow and groundwater flow) assume very different mechanisms for moving solutes, either laterally or vertically (Reeve *et al.*, 2000). The shallow flow model assumes that there is little vertical transport of solutes through the catotelm layer, and that the only mechanism for solute transport in the catotelm is diffusion (Devito *et al.*, 1997). Contrarily, the groundwater flow model assumes some vertical transport of both solutes and water through the peat matrix (Reeve *et al.*, 2000).

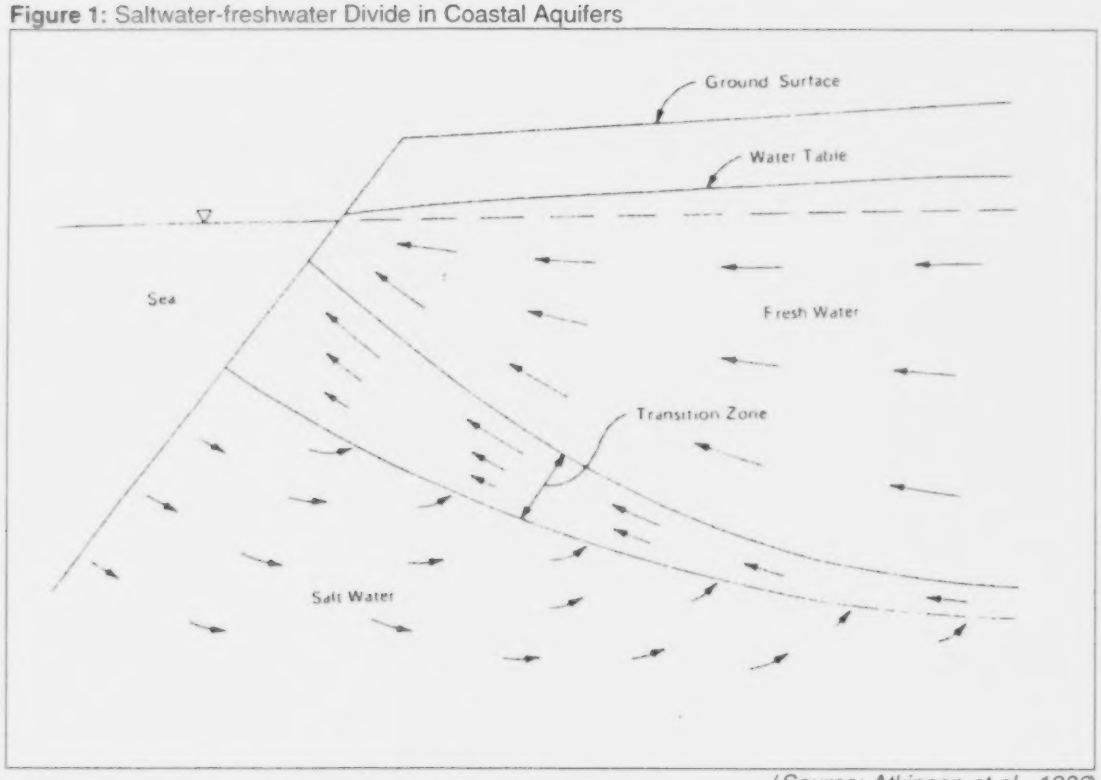
As with the flow of water, the transport of solutes is similarly affected by climatic variables such as precipitation, evapotranspiration, snowmelt and heavy spring rainfall events. The variability of solutes is partially determined by dilution from precipitation and snowmelt, and by concentration due to evapotranspiration (Hoag and Price, 1995; Price,

1994; Price and Woo, 1988). Wilcox (1986) found that solute declines within the 0 - 0.5 m layer were associated with increases in the 0.5 - 0.15 m layer, and vice versa (depending on precipitation or evapotranspiration events). The large hydraulic head created during snowmelt generally results in a downward movement of water and a flushing of solutes from the surficial peat layers. Wilcox (1986) observed the strongest declines in solute concentration of the surficial peat between the months of October and June, and concluded that the vertical movement of solutes by advection was a more dominant process than diffusion at his study site (Wilcox, 1986).

Saltwater Intrusion

Along sea coasts there is a subsurface divide between saltwater and freshwater (Soliman *et al.*, 1998; Atkinson *et al.*, 1986) (Figure 1). This zone of transition may be relatively narrow or wide, depending on the extent of the tidal influence (Fetter, 1994; Freeze and Cherry, 1979). As a more dense liquid, saltwater tends to force its way underneath freshwater, causing a density-dependent layering of groundwater (Fetter, 1994; Atkinson *et al.*, 1986).

Figure 1: Saltwater-freshwater Divide in Coastal Aquifers



(*Source: Atkinson et al., 1986*)

In a homogeneous unconfined aquifer under equilibrium conditions, the depth of saltwater below the surface has been calculated to be 40 times the depth of fresh water below the surface, using the Ghyben-Herzberg relation (Soliman *et al.*, 1998; Freeze and Cherry, 1979). As a result, a 1 m lowering of the water table in the freshwater aquifer will cause a subsequent 40 m rise in the elevation of the saltwater-freshwater interface (Freeze and Cherry, 1979). However, there are some questions about the assumptions that underlie the Ghyben-Herzberg relation, and it is thought to be too simplistic to provide a realistic estimate of the elevation of the saltwater-freshwater interface (Freeze and Cherry, 1979). Nonetheless, it does demonstrate that saltwater does not necessarily occur at the elevation of the mean sea level.

Saltwater intrusion occurs in areas where the freshwater aquifer has a hydraulic connection with the sea (Atkinson *et al.*, 1986; Freeze and Cherry, 1979). The saltwater-

freshwater divide will be relatively stable unless there is a hydraulic gradient created which removes freshwater from the aquifer. Such a gradient can be created either through drainage or pumping, and results in a mixing and diffusion of the divide (Atkinson *et al.*, 1986). When the hydraulic head is decreased by freshwater withdrawal or drainage, it draws saltwater into the aquifer due to the pressure gradient that has been created. Continued withdrawal will cause a continued rise in the elevation of the saltwater-freshwater divide.

Other Sources of Saltwater

Natural sources of saltwater contamination include extreme storms, atmospheric inputs and fossil salts. Extreme storms are an unpredictable and infrequent source of saltwater to coastal bogs. In addition, atmospheric sources, such as fog and precipitation, can be significant inputs of saltwater in coastal bogs. Price (1994) found salt concentrations in fog were ten times higher than the concentration found within rainwater. Similarly, Reynolds and Pomeroy (1995) found that, on average, there was a concentration of chlorides four to five times higher in fog than in rainwater. Fog can be a substantial input, of both solutes and water, to coastal bogs. The overall significance of fog as a source of salts depends upon the annual number of fog days in the region.

The mineral substrate underlying a bog can be one possible source of salts, particularly in coastal regions (Charman *et al.*, 1994; Fetter, 1994; Price and Woo, 1988). Such salts were deposited within the mineral layer at a time when that layer was exposed to seawater. As a result, areas with saline mineral substrates are often found to have high concentrations of salts with depth (approaching the mineral substrate layer). Price and Woo (1988) found that salinity in James Bay coastal marshes (with a peat soil) are more strongly affected by fossil salts in the underlying mineral sediments than from tidal flooding by

brackish estuarine water. Charman *et al.* (1994) found a similar trend, whereby chloride levels increased upon contact between the peat and marine-influenced glaciolacustrine clay.

1.1.3 Peatland Restoration

Goals and Objectives of Peatland Restoration

Cutover peatlands, once exhausted of their peat stores, are often left to regenerate without any associated management efforts. However, such sites can generally not support any substantial growth of peatland vegetation species, particularly *Sphagnum* mosses, due to the harsh growing conditions present (Rochefort, 2000). Cutover peatlands left to regenerate without any management actions will not recover the hydrological regime or peatland plant cover that would be expected in a natural bog (Rochefort, 2000; Van Seters and Price, 2001). Such inability to return to a natural state is predictable based upon the hydrological changes, many of which are irreversible, which result from drainage and from removal of the acrotelm (see section 1.1.1, Hydrological Effects of Drainage).

As a result, management actions must be undertaken if a cutover bog is to be returned to a state that even remotely approximates that of an undisturbed bog. 'Restoration' implies that management actions be undertaken in an attempt to return a site to a functional peat accumulating ecosystem (Price *et al.*, 2003; Rochefort, 2000; Wheeler and Shaw, 1995). Peatland researchers have devised three methods (ditch blocking, bund installation and straw mulch spreading), which are capable of partially restoring the hydrological regime of cutover bogs.

The objective of restoration varies, but is usually a combined product of "the perceived desirability of a particular option, its cost and possibility" (Wheeler and Shaw, 1995: 52). With respect to cutover peatlands, the long term objective is "to re-establish self-regulatory mechanisms that will lead back to functional peat accumulating ecosystems (PERG, 2003; also see Money *et al.*, in press; and Rochefort et al., 2003). In the short

term, there are two main objectives: the re-establishment of a typical peatland plant cover (including Sphagnum mosses), and the re-establishment of the hydrological regime (Rochefort et al., 2003; PERG, 2003).

Current Restoration Techniques

Ditch blocking, perpendicular to flow direction, creates open water ditch reservoirs which help to regulate water table fluctuations in the cutover peat (Schlotzhauer and Price, 1999). As a result, the open water ditch reservoirs increase the soil moisture within the surface peat layers. Typically, ditch blocking is the first and most obvious management action to take, since it is widely recognized that ditches cause drawdown of the water table. By blocking the ditches, it is expected that the water table will rise to its undisturbed state. However, field trials have shown that, when ditches are blocked without additional management actions, there is varied effectiveness. Price (1997) found that blocking ditches resulted in a water table elevation similar to that of a nearby undisturbed site, although Price *et al.* (2003) and Money *et al.* (in press) have reported that ditch blocking raises the water table but does not prevent water losses to runoff during periods of high water table.

Undisturbed bogs have the ability to trap snow in vegetation and in hollows; this snow will eventually melt in situ and provide a substantial water source to the bog (Ingram, 1983). Without a vegetated surface, a cutover bog does not have the ability to trap snow and to retain snowmelt, and hence this source of water is not present during the critical water deficit period later in the summer. To compensate, terraces and bunds can be installed to trap surface runoff during snowmelt and heavy rains. Terraces will allow the bog to maintain a higher and more spatially even water table than blocking ditches alone can achieve (Price *et al.*, 2003; Money *et al.*, in press). Bunds are generally placed along contour lines to create the terraced effect (Price *et al.*, 2003). Although this management

action does not mimic the natural topography of an undisturbed bog, it does assist in restoring the water balance.

When blocking ditches is coupled with the installation of bunds and terraces, the effect is a net improvement in the hydrology of the cutover bog, although it still does not fully mimic that of an undisturbed bog. Both of these management techniques are more effective when they are coupled with straw mulch placed on the peat surface. The straw mulch maintains adequate wetness to support the recolonization of *Sphagnum* species (Price, 1997; Money *et al.*, in press), which are spread over the cutover peat beneath the mulch (Quinty and Rochefort, 1997). The application of straw mulch provides shading of the peat surface and results in a reduction in the amount of evapotranspiration occurring. The reduction in evapotranspiration decreases pore water tension and increases soil moisture by 10 to 15% (when compared to an untreated surface) (Price *et al.*, 2003; Price, 1997).

The Pokesudie Exception

Despite the proven effectiveness of these three techniques at improving the hydrology of abandoned cutover bogs, they may not be useful at a cutover site such as that found on Pokesudie Island, N.B.. The hydrological conditions of the cutover bog on Pokesudie are complicated by the fact that the peat is contaminated with saltwater. Current restoration techniques are meant to restore soil moisture and water table elevation, not to control salinity levels. Salinity in the rooting zone will affect any plants that comprise the restoration effort; typically, bog plants are intolerant of saline water conditions. In the case of Pokesudie, the objective for restoration may not be the restoration of a *Sphagnum* dominated peat surface. Researchers at Laval University and Ducks Unlimited are investigating the potential for restoration of salt marsh plants on the cutover bog surface. This research paper provides the hydrological basis for further research and restoration efforts.

1.2 Research Question

This undergraduate thesis investigates the following question: What are the factors and processes that control salinity in the rooting zone at the Pokesudie cutover bog?

1.3 Research Justification and Objectives

No other research has studied storm-based saltwater contamination on a cutover bog, and research on solute transport in undisturbed bogs is minimal. Such research is particularly important for coastal harvested bogs, which are at a greater risk of saltwater contamination from either saltwater intrusion or from other contamination sources. As a result, it is imperative that there is an understanding of the implications of solute transport mechanisms for remediation and restoration activities.

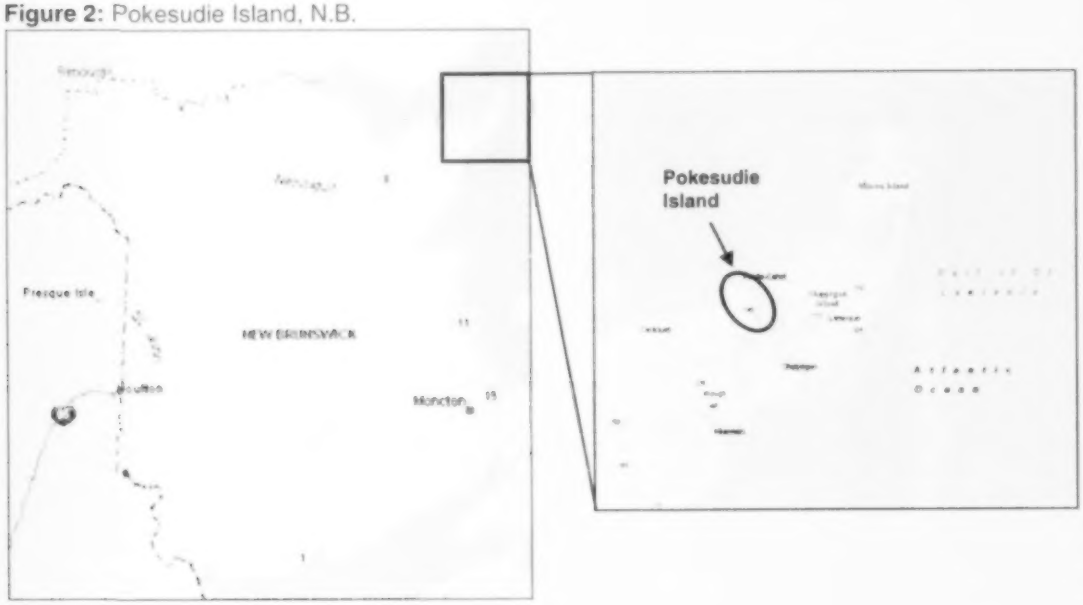
The objectives for this research are:

- *To characterize the functions and processes that control salinity in the rooting zone*
- *To characterize the basic hydrologic and climatic conditions of the study site*
- *To provide preliminary input for site restoration*
- *To provide recommendations for future research on site*

2.0 STUDY AREA

The study site is located on a harvested peat bog on Pokesudie Island, New Brunswick, Canada (47.8°N, 64.78°W), which lies at the northern tip of the Acadian Peninsula (Figure 2). The harvested bog is also known as Bog 600 on the New Brunswick Department of Natural Resources peatland inventory maps.

Figure 2: Pokesudie Island, N.B.



2.1 Local Geomorphology

Pokesudie Island is located within the Acadian Islands subdivision of the New Brunswick Lowlands physiographic region. The New Brunswick Lowlands are characterized by flat to gently sloping plains which slope in an easterly direction towards the ocean. Underlying the Lowlands is Pennsylvanian sandstone, which reaches a maximum thickness of 1000 m near the coast. Peat deposits are abundant along the coast of New Brunswick, from Miscou to Richibouctou (Rampton *et al.*, 1984).

The Acadian Islands subdivision includes Pokesudie Island, Shippegan Island and Miscou Island (Figure 2). These islands are relatively flat and poorly drained, and contain extensive areas of peat bogs. The coastlines are characterized by scarps (less than 5 m

high), spits and baymouth bars. The Acadian Islands were deglaciated approximately 13,200 years ago (Rampton *et al.*, 1984). After glaciation, this area was immersed under 30 m of seawater, and the duration of this immersion is predicted to be from one to three thousand years (Rampton *et al.*, 1984; Robichaud, 2000).

Pokesudie Island is covered primarily by organic sediments. These organic sediments are characterized as "peat, muck, minor silt and fine sand; generally 1 to 5 m thick; deposited in shallow basins and on poorly drained surfaces" (Rampton *et al.*, 1984). Other sediments occur around the fringe of Pokesudie Island, and include intertidal plains and salt marshes (generally over 2 m thick, primarily clay and silt); sand and silt plains (0.5 to 3 m thick); and beaches, bars and spits composed of sand and gravel (generally over 1 m thick).

2.2 Present Site Conditions

At present, the study site on Pokesudie Island is a raised coastal peat bog, typical of the Acadian Peninsula. This bog is currently under management by Lameque Quality Group, who acquired the land in 1988 (Chiasson and Saulnier, no date). Approximately 140 hectares (350 acres) have been harvested and/or abandoned (Chiasson and Saulnier, no date). The site is not currently in operation due to contamination by saltwater which occurred in 2000 (see section 2.3).

The harvested area has been drained by ditches, spaced approximately 25 to 30 meters apart, which feed into several main ditches. These ditches direct water towards a main pump in the western area of the site; this pump drains the excess water into the ocean. The pump is not currently in operation. As a result, the drainage ditches show only a minimal flow towards the pump due to gravitational forces. Areas in the interior of the harvested area were the first to be harvested, and hence the first to be abandoned once the peat deposits were exhausted. The ditches in these areas are generally is a state of disuse and collapse, and the peat depth ranges from 0.5 to 1.0 m. Two fields in the north and

eastern areas of the harvested site were still in operation at the time of contamination and closure in 2000, and hence the ditches are still intact. The peat depth in these fields varies from approximately 1 to 4 m.

The Pokesudie harvested peatland also includes test plots for a cranberry farming operation, which is an attempt to provide a reclamation operation for the abandoned bog areas. Although these plots were also contaminated by saltwater in 2000, farming efforts were recommenced in 2003 to recover the cranberry operation (Chiasson, 2003, pers. comm.).

The harvested bog is surrounded by ocean on three sides, including areas of mineral islands, open shoreline and salt marsh. The maximum elevation of this site is 4 m a.s.l., although there is a relatively flat topography. Most of the current topographic features are the result of peat harvesting operations (see Appendix A).

On average, there is approximately 1058 mm of annual precipitation, 30% of which falls as snow (Bathurst, NB station, Environment Canada, 2004a). There is also an average of 37 fog days per year in the surrounding region (Environment Canada, 2004b). The tide elevation ranges from 0.0 to 1.7 m a.s.l. (Fisheries and Oceans Canada, 2004).

2.3 The Storm Surge, 21 January 2000

On 21 January 2000, a severe storm warning was issued by Environment Canada for the entire Canadian maritime coast, from Nova Scotia to Quebec. Snow accumulations were predicted to be in excess of 30 cm, and over 100 km/hr winds were expected (Chiasson and Saulnier, n.d.). The intense winter storm hit the coast during a period of high tides and a full moon, resulting in a 1.2 to 2.0 m storm surge and record-breaking flooding along the eastern coast from Nova Scotia to New Brunswick (OCIPEP, 2004). In many locations, including Pokesudie Island, this surge forced winter ice onto shorelines (OCIPEP, 2004; Chiasson and Saulnier, n.d.). This winter storm was accompanied by up to 70 cm of

snow, high winds and a -40°C wind chill. Total damages for the region were estimated at $20 million (in 2000 dollars) (OCIPEP, 2004).

At the Pokesudie Island harvested bog, the main damage occurred on the western and northern fields (including field C2, the study site of this research project) (Chiasson and Saulnier, n.d.). The roadway between fields C1 and C2, as well as the floodgate control on the pump and the dykes behind the cranberry fields, prevented the surge from extending into the centre of the harvested site. At the time of this saltwater inundation, the peat was frozen. The resultant flooding was typically 0.3 to 0.7 m (1 to 2') deep and included saltwater, slush and drift ice (see Figure 3 and Figure 4) (Chiasson and Saulnier, n.d.).

Figure 3: Drift Ice, January 2000

Photo credit: Lameque Quality Group, Ltd.

Figure 4: Saltwater Slush, January 2000

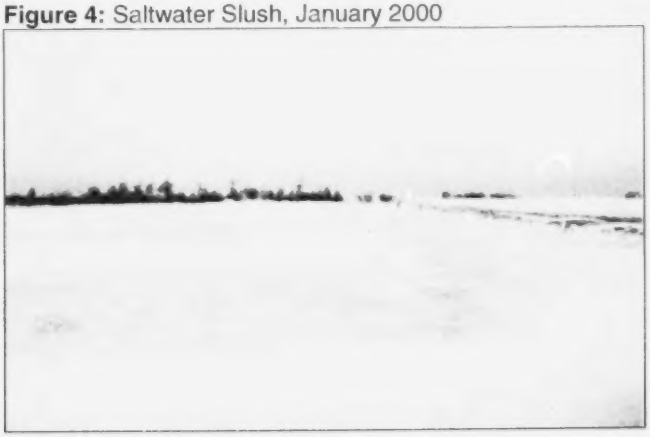


Photo credit: Lameque Quality Group, Ltd.

Lameque Quality Group (LQG) took preventative actions to minimize or localize saltwater contamination of the peat resource. On 24 January 2000, the main pump was de-iced and started to remove excess water from field C2 (Chiasson and Saulnier, n.d.). In addition, LQG attempted to remove snow from the contaminated areas (Figure 5). However, it was determined that such snow removal attempts were not an economical or efficient use of resources, and were ceased on 2 February 2000. Tests showed that, despite pumping and cleanup attempts, the frozen peat was becoming increasingly saline, even as early as 9 February 2000 (Chiasson and Saulnier, n.d.).

Figure 5: Snow Removal, 1 February 2000

Photo credit: Lameque Quality Group, Ltd.

Once the summer harvesting season began, Lameque Quality Group once again began the pumps to prepare the site for harvesting, in the hopes that some areas of the peatland could be successfully harvested (Saulnier, 2003, pers. comm.). However, tests still showed that the peat was too saline for use in commercial peat moss mixes (LQG, 2000a; LQG, 2000b; LQG, 2000c; Chiasson and Saulnier, n.d.). As a result, the site was closed to further harvesting, and research is currently underway to determine methods to successfully restore or reclaim this site for other uses. Such research was commenced in 2003 as a joint operation between Lameque Quality Group and the Peatland Ecology Research Group (Laval University and the University of Waterloo).

3.0 METHODS

3.1 Site Layout

This research was concentrated in field C2, the northernmost field in the Pokesudie harvested peatland. There is additional instrumentation in the neighbouring field C1 and in the natural zone for comparison. (see Appendix B for Pokesudie field codes). Testing conducted by Lameque Quality Group had indicated that field C2 was heavily affected by the storm surge (LQG, 2001; LQG, 2000b; Chiasson and Saulnier, n.d.).

Two transects were installed with nests of piezometers (capped, partially slotted), wells (uncapped, fully slotted), and other instruments (Figure 6). In total, these transects contain ten nests of instruments. They have been labelled from north to south, from 'n01' to 'n10'; the 'n' represents 'nest' and the two digit number represents the nest number. The harvested zone transect extends from just beyond the northern edge of the harvested area towards the centre of the harvested area, and contains seven nests of instruments (n01 to n07). The primary focus of this transect is field C2, where four of the seven nests are located (n02 to n05). Two additional comparison nests are located in field C1 (n06 and n07), while one comparison nest (n01) is located just north of C2, in the thin fringe of natural bog beyond the harvested site. The natural zone transect occurs slightly east of field C2, and contains three nests of instruments (n08 to n10). This transect was installed, parallel to the harvested zone transect, to provide comparative data for the harvested zone transect. In addition to these two transects, a meteorological station was set up to provide automatic monitoring of several climatic and hydrologic variables.

Figure 6: Harvested and Natural Transect Locations, Aerial Image

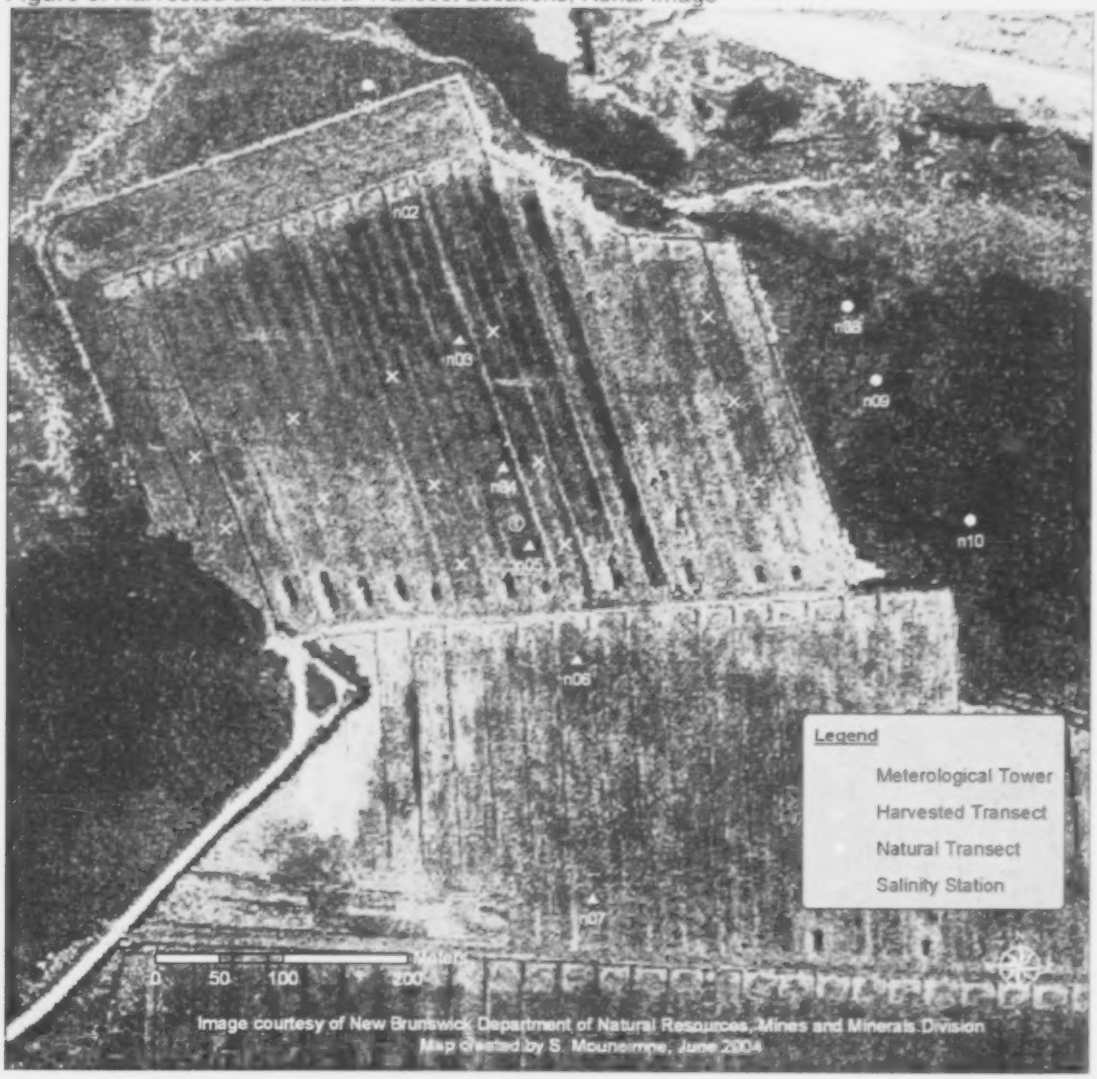


Table 1 provides a summary of the depths of piezometers that can be found at each station. At each of the nests, there is a well (100 cm deep) and an array of piezometers from 50 to 150 cm deep, on a 25 cm interval. The stated depth refers to the depth at the centre of the slotted intake. There are fewer piezometers in the nests with shallower peat, such as n06 and n07. The natural zone stations have piezometers that range from 25 to 100 cm, on a 25 cm interval, due to shallow peat. All piezometers, with the exception of

those at the 150 cm depth, have a 15 cm slotted intake. The 150 cm piezometers have a 25 cm slotted intake.

Table 1: Piezometer Depths at Each Nest

	Piezometer Depth (cm)							
Nest	**25**	**50**	**75**	**100**	**125**	**150**	**deep**	**well**
n01		X	X	X	X	X		X
n02		X	X	X	X	X	X	X
n03		X	X	X	X	X		X
n04		X	X	X	X	X	X	X
n05		X	X	X	X	X		X
n06		X	X					X
n07		X	X	X			X	X
n08	X	X	X	X				X
n09	X	X	X	X				X
n10	X	X	X	X				X

While most nests contained only a well and several piezometers of varying depths, three of the ten nests were designated as 'detailed nests', meaning that there was additional instrumentation at these nests. They were designed to provide a more complete set of hydrological data, and hence were monitored more frequently than the other seven nests. Two detailed nests were located in field C2 (n02 and n04), while one was located in field C1 (n07).

In addition to the array of piezometers and the well, the detailed nests contained a deep drive-point piezometer, an array of tensiometers, and a subsidence bar. The deep (drive-point) piezometer was installed into the sand layer below the peat. The tensiometers were installed at 2, 5, 10, 20 and 30 cm depths. The subsidence bar was hammered into the sand below the peat to allow a monitoring of the relative surface elevation of the peat.

The location for the harvested transect was selected for a number of reasons. It was decided that the transect should be located in such a way that it can pass through both fields C2 and C1. However, extensive flooding in field C2 in early May (Figure 7) left few options available that would satisfy the C2-C1 transect requirement. As a result, the

ntransect selected is one of the few areas in C2 that was only partially under water in early May. At that point in time, it was unknown how late this surface water would persist, and hence it was not deemed useful to install piezometers in the peat below this ponded water. As a result, the transect is on a slightly higher elevation than the remainder of field C2 (the transect is located in the centre of Figure 8, extending towards the horizon). However, this selective placement of the transect was required due to the site conditions at the time of installation.

Figure 7: Surface Water Ponding, 3 May 2003, Field C2 (view facing north)

Photo credit: J.Price

Figure 8: Harvested Transect Location, 4 May 2003, Field C2 (view facing north)

Photo credit: S. Mouneimne

The meteorological station contains several instruments to measure climatic and hydrologic variables. Two wells monitor the water table elevation, water temperature and

electrical conductivity. Both ground heat flux (Q_G) and available energy (Q^*) were also monitored, as was the ground temperature at 5 cm from the surface. Finally, a tipping bucket rain gauge and a manual rain gauge monitored precipitation at the site.

Further details about specific methodology, instrument dimensions and installation methods can be found in section 3.2. Both field and lab methods are detailed.

3.2 Research Methods

Research was conducted between 6 May and 14 August 2003. The following sections provide field and lab methods, as well as the monitoring timing for individual variables. Conversion and analysis calculations are also included in this section. Instrument specifications (operation limits, accuracy, resolution and measurement ranges) can be found in Appendix C.

3.2.1 Climate Data

Climatic and hydrologic variables were monitored at the meteorological station using a Campbell Scientific Instruments (CSI) CR10X Datalogger. The program for this datalogger has been included in Appendix D. Continual data collection occurred from 6 May to 14 August 2003, with the exception of 19 to 21 July 2003. The datalogger battery was stolen on 19 July, and a new battery was installed on 21 July 2003.

Air, water and soil temperature (at 5 cm) were monitored using the CSI Temperature Probe 107 and 107B. Two wells were installed at the meteorological station to monitor electrical conductivity and water level. Electrical conductivity was monitored using the CSI Conductivity and Temperature Probe CS547A (with the A547 Interface), while water level was monitored using a float connected to a potentiometer, and recorded by the datalogger. Net radiation (Q^*) was measured using the Radiation Energy Balance System (REBS) Q^*6.7.1 net radiometer, while ground heat flux (Q_G) was monitored at 5 cm from the soil

surface with a REBS HFT – 1 heatflux plate. Precipitation was monitored using a tipping bucket rain gauge (TE525).

Air temperature and precipitation data from the Pokesudie meteorological station were compared with the 30 year average values from the Bathurst, N.B. Environment Canada station (47° 37' N, 65° 39' W) (see Environment Canada, 2004a). Bathurst is the nearest coastal station that has published 30 year average data.

Radiation and Potential Evapotranspiration

The radiometer measures Q*, the sum of incoming radiation minus outgoing (reflected) radiation. Q* readings are affected by wind speed, which cause a reduction in the measured value by up to 5.9% when the wind speed exceeds 7 m/s (REBS, 1995). Radiation (Q*) and ground heat flux (Q_G) data were used, along with air temperature, to calculate equilibrium evapotranspiration, using the Priestley-Taylor (1972) equation. An alpha value of 1.25 was used, as recommended by Price (1997) for cutover (harvested) peatlands, to adjust equilibrium evapotranspiration to actual evapotranspiration. This alpha value is close to that suggested by Priestley and Taylor (1972) to represent potential evapotranspiration ($\alpha = 1.26$).

Precipitation

Precipitation was monitored both automatically (using the tipping bucket rain gauge) and manually. The manual rain gauge was used to verify the values obtained from the automatic rain gauge. The manual gauge was checked every site visit, typically three to five times per week. The manual gauge had a resolution of 0.2 mL and a maximum capacity of 25 mL. Any rainfall in excess of 25 mL was captured by the overflow bucket.

3.2.2 Frost Table

The top of the frost table was measured every site visit, three to five times per week. A 1.2 m (4') section of rebar was pushed into the peat until the frost table was reached. The

depth of the frost table was measured in three randomly selected locations (in areas which were not compacted by walking). The frost table was recorded as 'patchy' once the rebar could pass through 1 m of frost-free peat. In these instances, three measurements were still taken, even if no frost was found in some of the measurements.

3.2.3 Peat Characteristics

Specific Yield and Bulk Density

Specific yield and bulk density were measured in a peat core taken near n03 on 22 July 2003. The peat core was transported to the University of Waterloo Wetlands Hydrology Lab and frozen. Tests for specific yield and bulk density were conducted in two trials, on 22 to 24 January 2004 and on 10 to 12 February 2004. The peat core was sliced into 5 cm blocks to provide comparable data for the salinity and chloride measurements taken on a second core from the same nest. Three centimetre deep cylinders of peat were cut from these 5 cm samples with a hole-saw. The top and bottom one centimetre of sample was trimmed to obtain the desired 3 cm depth. Two trials were conducted on two sets of cores: one used a ring with a radius of 3 cm (84.8 cm^3 volume) and one used a ring with a radius of 2.7 cm (68.7 cm^3 volume).

In Trial 1, the samples were defrosted in the ring, in a sealed container. Once defrosted, the sample was trimmed to fit the ring volume. These samples were wrapped in mesh and set to soak for 24 hours. In Trial 2, the samples were defrosted in the ring, *in water*. These samples were trimmed after 24 hours of soaking and defrosting, then set to soak for another 24 hours. The second trial was conducted to determine if there was swelling of the peat upon immersion in water, which would have caused a change in volume of the sample. Trimming the sample after saturation was expected to minimize this volume change problem.

All samples were weighed after 24 hours of immersion in water (M_{sat}). They were set on a rack to drain for 24 hours, and reweighed after this draining period (M_{drain}). Finally, the samples were dried for 24 hours, and weighed once dry (M_{dry}). The weight of the container and the mesh was subtracted for all calculations. The following calculations were used for specific yield and bulk density:

$$Sy = [(M_{sat} - M_{drain})/ \rho_w]/(M_{sat}/\rho_w) \quad (1)$$

$$\theta_{BD} = M_{dry} / V_{sample} \quad (2)$$

Where:
Sy = specific yield
M_{sat} = saturated mass (g)
M_{drain} = drained mass (g)
ρ_w = density of water (1 g cm^{-3})
V_{sample} = original sample volume (cm^3)

Hydraulic Conductivity

Hydraulic conductivity (K_h) was measured at all defrosted piezometers and wells in the harvested zone over several days between 21 July and 6 August, as well as at n08 in the natural zone for comparison. Appendix E contains a table of the testing dates for K_h. Hydraulic conductivity was only measured once at each piezometer and well for the summer field season.

Saturated hydraulic conductivity was measured using the bail test and Hvorslev's (1951) method. Saturated hydraulic conductivity was calculated using the following formula:

$$K_h = [r^2 * \ln(L/R)] / (2 * L * T_o) \quad (3)$$

Where:
K_h = saturated hydraulic conductivity (m/s)
r = internal pipe radius (m)
R = external pipe radius (m)
L = length of slotted pipe below the water table (m)
(see piezometer and well dimensions in Appendices F and G)
T_o = time lag (s)
= occurs when $(H-h)/(H-H_o) = 0.37$
H = initial measured water level relative to a datum (m)
h = water level at a point in time (m)
H_o = water level immediately following bailing (m)

Subsidence and Strain

Subsidence was measured as the relative elevation of the peat surface with respect to an arbitrary datum. This datum was corrected to meters above mean sea level using a site survey. Subsidence was measured twice per week at the three detailed nests (n02, n04 and n07). Subsidence was only measured in the harvested areas.

A length of rebar (2.4 m at n02 and n04, 1.2 m at n07) was hammered down into the sand layer below the peat, to anchor it. The rebar is surrounded by a ½" C-PVC pipe to ensure that expansion and contraction of the peat layers does not move the rebar. An L-bracket was attached to the top of the rebar. Changes in the relative elevation of the peat surface were monitored using measurements of the distance between the L-bracket and the peat surface.

The subsidence values can be used to calculate the relative strain on the peat during any given period of time. Strain is the relative change in thickness of a layer due to compression or swelling. In this system, volume change was determined in the layer of peat above the frost table. The thickness of this layer is continually increasing over the summer as the frost surface retreats. Strain can thus be calculated as follows:

$$Strain = (\Delta_{SUBSID} / T) / D_F \qquad (4)$$

Where:
Strain = relative change in layer thickness (unitless)
Δ_{SUBSID} = change in subsidence since last measurement (cm)
T = amount of time between measurements (days)
D_F = frost depth relative to the peat surface (cm)

3.2.4 Water Table

Nests

Water table was measured in defrosted piezometers and wells once per week at most nests, and twice per week at detailed nests. Water table was monitored using a blow pipe. All piezometers and wells were made from Schedule 80, 1" PVC tubing. The dimensions of the piezometers can be found in Appendices F and G. The dates of

installation, defrost and replacement can be found in Appendix H. Some piezometers and wells were replaced due to a torn mesh that allowed peat to enter through the slotted area and settle at the bottom of the well or piezometer.

Automatic Float-pot Well

Water table was also measured at the meteorological station in the float-pot well. The datalogger continually recorded the height of the water table every 30 minutes. Manual measurements were also taken from the peat surface to the height of the water table every site visit, three to five times per week.

The well was originally dug to a depth of approximately 75 cm, although with time this depth was reduced to approximately 60 cm due to subsidence and siltation. The diameter of the well is approximately 20 cm, and the well is lined with a perforated flexible metal stove pipe to ensure that the sides of the well do not collapse. The float-pot recorder was affixed to a 3.0 meter (10') angle iron which was hammered into the sand layer below the peat.

The float-pot output is recorded in mV. The manual measurements were used to convert this mV value into meters above sea level. The manual measurements were corrected for surface subsidence. Data is missing from the period of Julian day 189 to 202, when the well was dry and the datalogger battery was stolen.

3.2.5 Electrical Conductivity, Salinity and Chlorides

Wells, Piezometers and Precipitation

Electrical conductivity (EC) and salinity were measured in both the field and in the lab using the WTW Conductivity Handheld Meter (LF 330) with Standard Conductivity Cell – TetraCon 325. The EC and salinity of piezometers and wells was monitored once per week during the field season. Water was purged from wells and piezometers one day prior to testing. The datalogger well also provided continuous monitoring of EC, which was verified

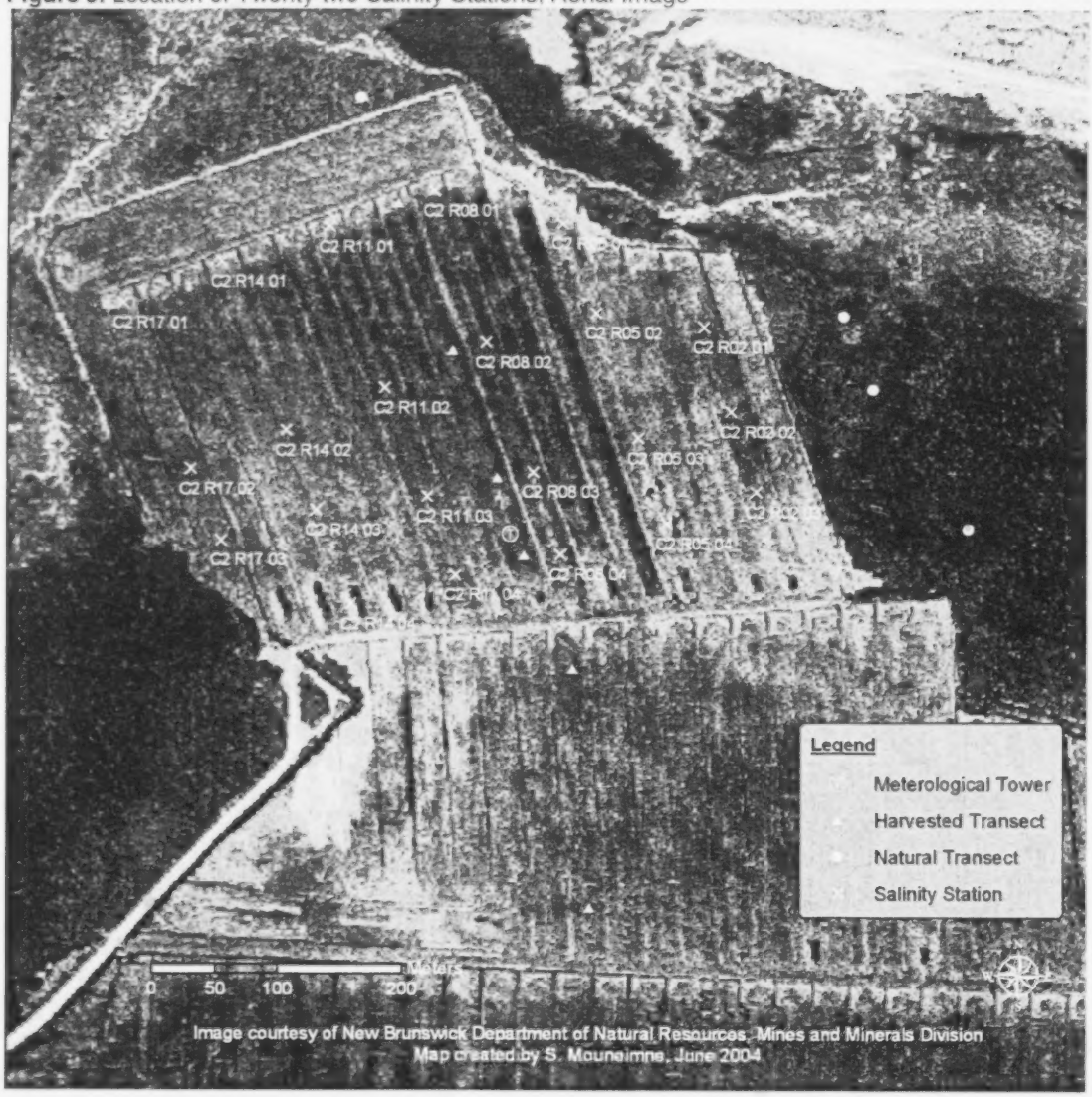
by manual measurements made at every site visit, three to five times per week. In addition, the EC and salinity of precipitation water was monitored for every rain event over 5 mm.

Surface Peat Samples

Blocks of peat 3" by 3" by 10" deep were removed at nests in the harvested transect and at salinity stations. These peat samples were taken in the harvested transect (6 stations) once per week, and at 22 stations throughout field C2 once every other week (Figure 9). The 10" deep peat blocks were divided into three 3" segments (0-3", 3-6" and 6-9" deep), placed in labelled Ziploc bags and transported to the Lameque Quality Group (LQG) laboratory for testing. These three depths were used in order to be consistent with testing conducted by LQG between 2000 and 2002.

In the lab, water was squeezed from these samples using a vacuum flask. This water was immediately sampled for pH, EC and salinity. EC and salinity were tested using both the WTW Conductivity Handheld Meter and the meter available in the LQG lab. Water samples were retained and shipped to the University of Waterloo Wetlands Hydrology Lab for chloride testing (see method below).

Figure 9: Location of Twenty-two Salinity Stations, Aerial Image



Deep Peat Cores

Four deep peat cores were extracted from n03 and n05, to depths of 50 to 100 cm (either to the base of the peat layer or to the top of the frost layer). Samples were also taken from the sand layer, using a cylindrical agricultural corer, to depths of 125 to 205 cm. Three cores were taken at n03: one immediately adjacent to the ditch, one approximately ten metres from the ditch, and one in the centre of the baulk (approximately 15 meters from the ditch). One sample was taken at n05 for comparison purposes.

These cores were sliced into 5 cm layers and placed in labelled Ziploc bags for transport to the Lameque Quality Group (LQG) laboratory for testing. Water was extracted and tested from these peat samples using the same vacuum method as the surface peat samples. The water samples were similarly retained and shipped to the University of Waterloo Wetlands Hydrology Lab for chloride testing (see method below).

Samples taken in the sand layers using the agricultural corer were too small to extract enough water for testing. As a result, water was added to the samples to create a saturated paste. Sufficient water was added to create a paste that glistened, did not stick to the sides of the container, and yet did not flow too freely. The paste was left for 24 hours before the water was extracted and tested for EC and salinity.

However, one step in the paste process was missed: the samples were not dried prior to the addition of water. As a result, the dilution ratio could not be determined by direct calculations. Therefore it must be assumed that the bulk density and porosity of the samples is 1.6 and 0.4, respectively, based on standard values for sands (Freeze and Cherry, 1979). The following calculations were then performed to obtain the undiluted salinity of the sample:

1. $V_{sample} = M_{sample} / \theta_{BD}$ **(5)**
2. $M_{w(original)} = \Phi * V_{sample} * \rho_w$ **(6)**
3. $Dilution\ factor = M_{w(added)} / (M_{w(added)} + M_{w(original)})$ **(7)**
4. *Undiluted salinity = measured salinity / dilution factor* **(8)**

Where:

V_{sample}	= sample volume (cm^3)
M_{sample}	= sample mass (excluding container) (g)
θ_{BD}	= assumed bulk density (g cm^{-3})
$M_{w(original)}$	= original mass of water (prior to dilution) (g)
Φ	= assumed porosity
ρ_w	= density of water (1 g cm^{-3})
$M_{w(added)}$	= mass of water added to sample to create paste (g)

Chloride Testing

Chloride concentrations were tested using a VWR Combination Chloride Electrode, which was stored daily in a 1,000 ppm standard solution to prevent drifting of electrode readings. A set of standard solutions were created (see Appendix I), with known concentrations of chloride (10, 100, 1000, 10000 and 100000 ppm), to provide a conversion equation from mV (the output) to ppm. The mV readings for each standard were plotted against the ppm concentration. A straight line relationship indicated a useable set of standards. Peat water samples were tested in groups of twenty, in a random order. The standards were re-tested after the 20th sample (approximately once every hour) to ensure that the electrode did not drift. A new mV-ppm relationship was plotted for each set of samples, to convert the water sample readings (mV) into chloride concentrations (ppm). Every effort was made to ensure that contamination of these standards did not occur. Deionized water was used for standard creation and for rinsing.

3.2.6 Pore water pressure

Pore water pressure was determined using tensiometer readings measured at the detailed nests twice per week. Each detailed nest contained an array of five tensiometers at the 2, 5, 10, 20 and 30 cm depths. The installation date for these tensiometers was dependent upon the frost depth. The 5 and 10 cm tensiometers were installed on Julian day 140, the 20 cm depth was installed on day 170, and the 30 cm depth was installed on day 181. The 2 cm depth was installed on day 188, as a late addition to the array. The 2, 5 and 10 cm tensiometers are L-shaped, while the 20 and 30 cm tensiometers are straight. A Soil Measurement Systems Tensimeter was used to measure the pressure (in mbar) in the air space within the tensiometers.

Appendix J contains a diagram showing the dimensions of each tensiometer type, and the variables used to calculate pore water pressure. The following equation was used to calculated pore water pressure:

$$\Psi = \Psi_{gauge} + h - z_{ten} \qquad (9)$$

Where:

Ψ = pore water pressure (cm)

Ψ_{gauge} = pressure reading from gauge (cm)
= conversion of gauge reading (mbar) to cm: 1 mbar = 1.0197162 cm of water

h = distance between midpoint of porous cup and height of water in tensiometer (cm)

z_{ten} = depth of tensiometer (cm) (2, 5, 10, 20 or 30 cm)

In addition, the gradient for two tensiometers is calculated as the change in pressure divided by the change in depth (the vertical distance between two tensiometers).

4.0 RESULTS

4.1 Climate

4.1.1 Air Temperature

Table 2 shows the mean, maximum and minimum air temperatures recorded at the meteorological station in the Pokesudie harvested peatland, from 9 May to 14 August 2003. Table 3 shows the mean, maximum and minimum air 30 year average temperatures for the Environment Canada station at Bathurst, New Brunswick (47° 37' N, 65° 39' W) (Environment Canada, 2004a).

Table 2: Pokesudie Climate Statistics, 2003

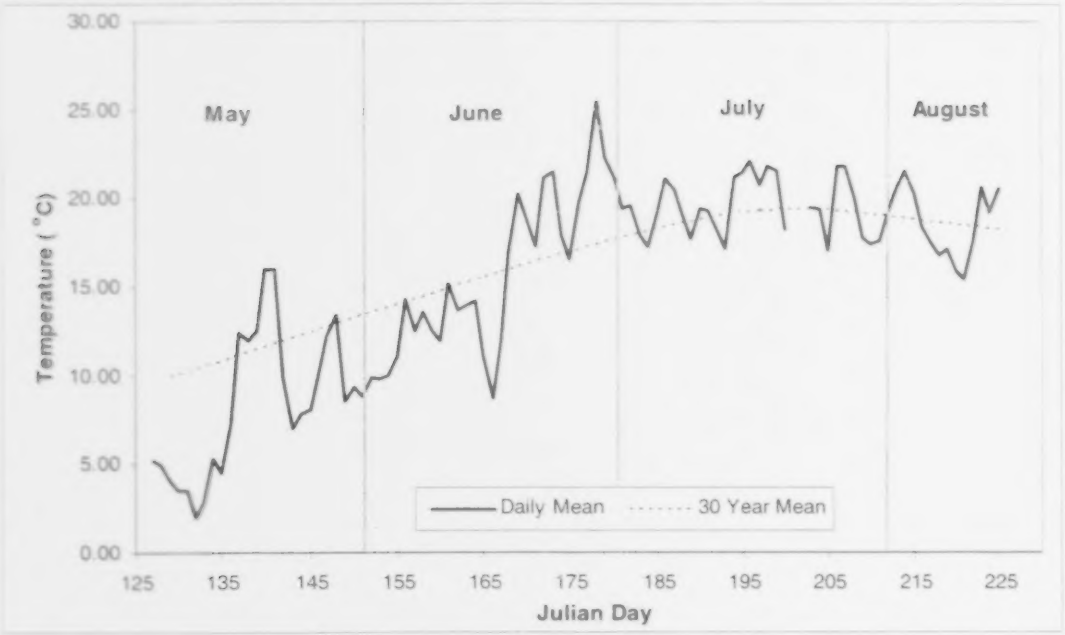
	May 9 to 31	*June*	*July*	*Aug 1 to 14*
Daily Mean Temp (°C)	8.3	15.8	19.5	18.6
Average Daily Max Temp (°C)	12.9	21.3	24.3	23.1
Average Daily Min Temp (°C)	4.0	10.8	15.6	15.1
Extreme Max Temp (°C)	27.4	32.3	30.1	28.7
Extreme Min Temp (°C)	-1.6	5.3	12.6	13.0
Total Precipitation (mm)	59.8	105.7	78.7	36.1

Table 3: Bathurst, N.B. 30 Year Mean Climate Statistics

	May	*June*	*July*	*August*
30 Year Average Daily Mean Temp (°C)	9.9	15.8	19.3	18.2
30 Year Average Daily Max Temp (°C)	15.4	21.4	24.7	23.4
30 Year Average Daily Min Temp (°C)	4.2	10.2	13.8	12.9
Extreme Max Temp (°C) *(year)*	32.2 *(1972)*	34 *(1983)*	36.5 *(1983)*	35.0 *(1975)*
Extreme Min Temp (°C) *(year)*	-6.1 *(1972)*	-1.0 *(1990)*	5.0 *(1989)*	2.0 *(1982)*
30 Year Average Precipitation (mm)	78.5	83.5	99.0	101.6

June, July and August at Pokesudie showed similar average values to the Bathurst, N.B. 30 year mean. However, May was colder than average, particularly since the May 1 to 8 period is not included in this calculation. Figure 10 provides the daily mean temperatures from 9 May to 14 August 2003 at Pokesudie.

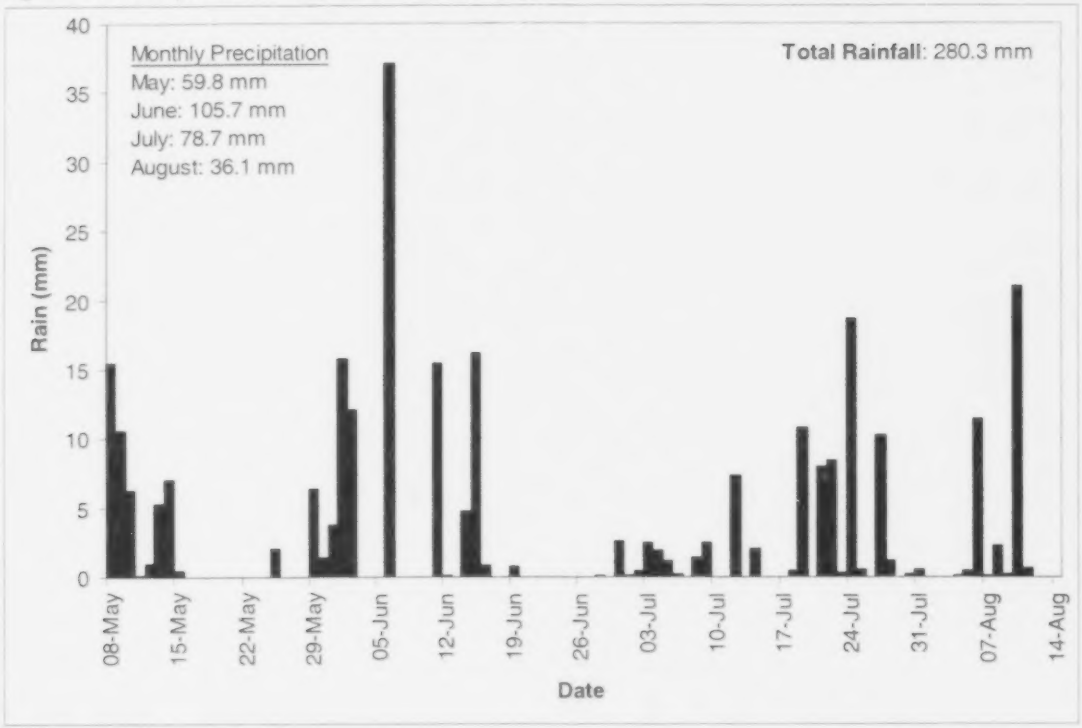
Figure 10: Daily Mean Air Temperature, 2003



4.1.2 Precipitation and Evaporation

The Pokesudie peatland received more precipitation than average in June (by 22.2 mm), and less than average in July (by 20.3 mm) (see Table 2). Assuming that the same rate of precipitation fell from May 1 to 7 as fell from May 8 to 31, May can be assumed to be an average month with a predicted total precipitation of 80.3 mm. Using the same assumption about August, it could be predicted that August was drier than normal. In total, 280.3 mm of rain fell between 8 May and 14 August 2003 (see Figure 11).

Figure 11: Precipitation, 8 May to 14 August 2003

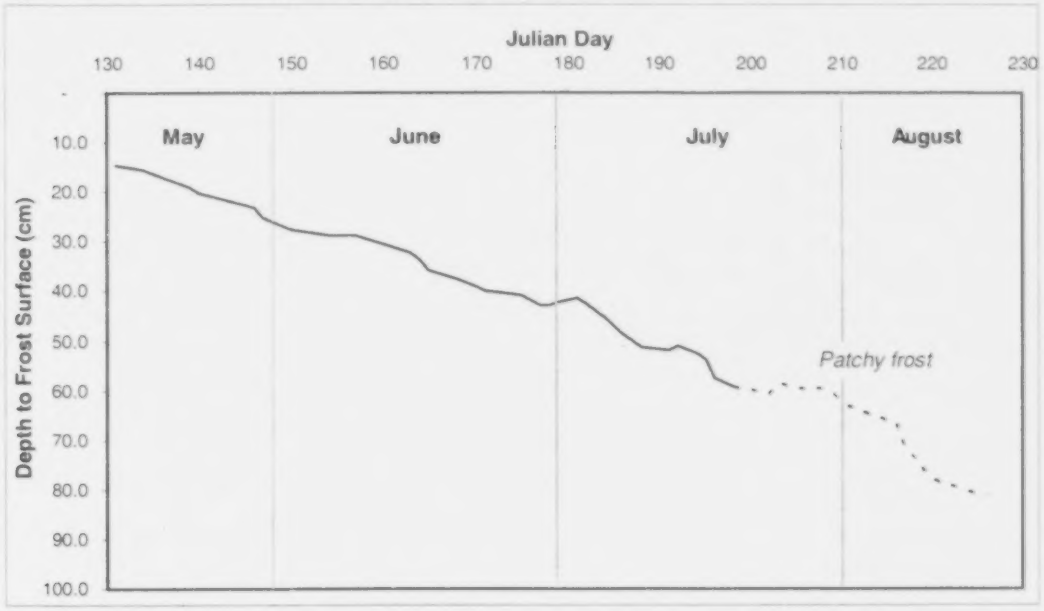


Evapotranspiration was calculated for the site using the Priestley-Taylor (1972) method, based on the air temperature and the amount of radiation energy that was available for evapotranspiration, and $\alpha = 1.25$ (Price, 1997). The cumulative evapotranspiration from 7 May to 14 August 2003 was 303.8 mm.

4.2 *Frost Table*

The depth of the frost table was monitored from 11 May to 14 August 2003. On 11 May, the frost table was within 15 cm of the peat surface. The frost table retreated by 0.8 cm d^{-1} on average until 17 July, when frost was found to be patchy (see Figure 12). Appendix H shows the dates of defrost for all piezometers and wells, since the level of frost had direct implications on the ability of water to flow freely within the piezometers.

Figure 12: Frost Table Depth, 11 May to 14 August 2003



4.3 *Peat Characteristics*

4.3.1 Specific Yield and Bulk Density

Values from Trial 2 will be used for data analysis, although Trial 1 data has been included for comparison purposes. Both trials were conducted on the same peat core, so the values would be expected to be comparable (see Table 4). The mean bulk density for all depths is 0.09 g cm^3, with a range of 0.07 to 0.13 g cm^3. The mean specific yield is 0.23, with a range of 0.20 to 0.28. Both bulk density and specific yield are relatively constant with depth (see Figure 13 and Figure 14 Figure 14). There is a very weak relationship (r^2 = 0.078) between specific yield and bulk density.

Table 4: Bulk Density and Specific Yield Statistics

	BULK DENSITY (g/cm^3)		*SPECIFIC YIELD*	
	Trial 1	Trial 2	Trial 1	Trial 2
Mean	0.09	0.09	0.21	0.23
Standard Deviation	0.02	0.02	0.02	0.02
Coefficient of Variation	0.18	0.21	0.12	0.10
Maximum	0.12	0.13	0.27	0.28
Minimum	0.07	0.07	0.18	0.20

Figure 13: Specific Yield by Depth

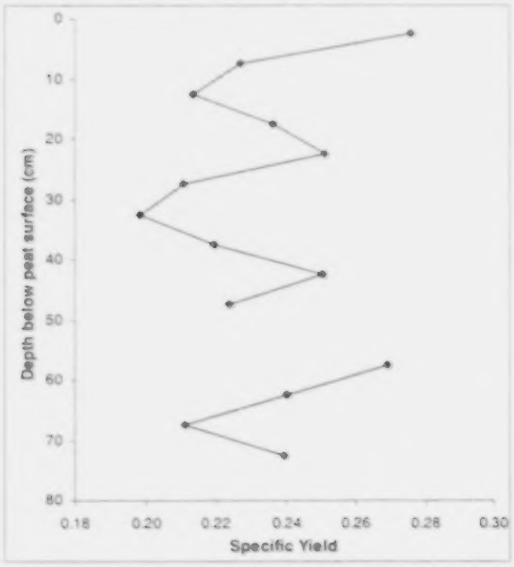
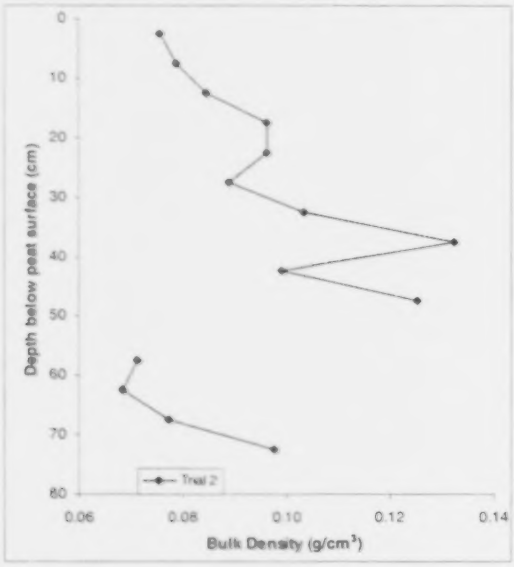


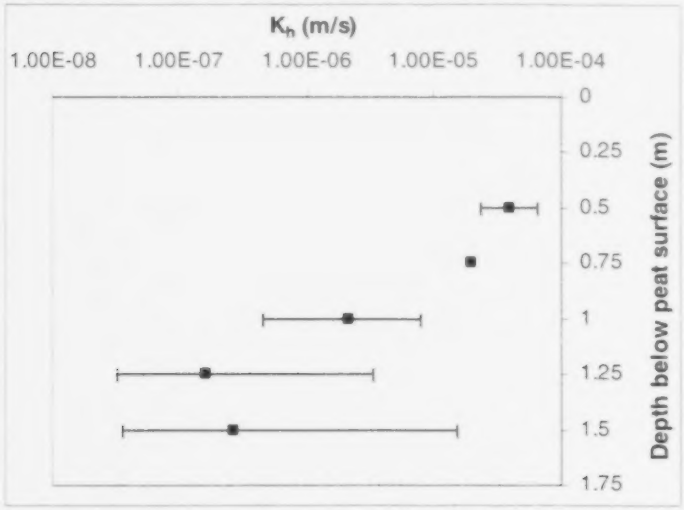
Figure 14: Bulk Density by Depth



4.3.2 Hydraulic Conductivity

Figure 15 shows the geometric mean hydraulic conductivity (K_h) by depth, for all piezometers of the same depth in field C2. The bars indicate the maximum and minimum values for K_h. Geometric means for the 100, 125 and 150 cm depths are calculated using four piezometers, while the 75 cm depth uses only one piezometer and the 50 cm depth uses two. There are less K_h values in the geometric means for the 75 and 50 cm depths because many of these piezometers were frozen or dry at the time of measurement (see Appendix H for defrost dates). In general, hydraulic conductivity decreases with depth (see Figure 15).

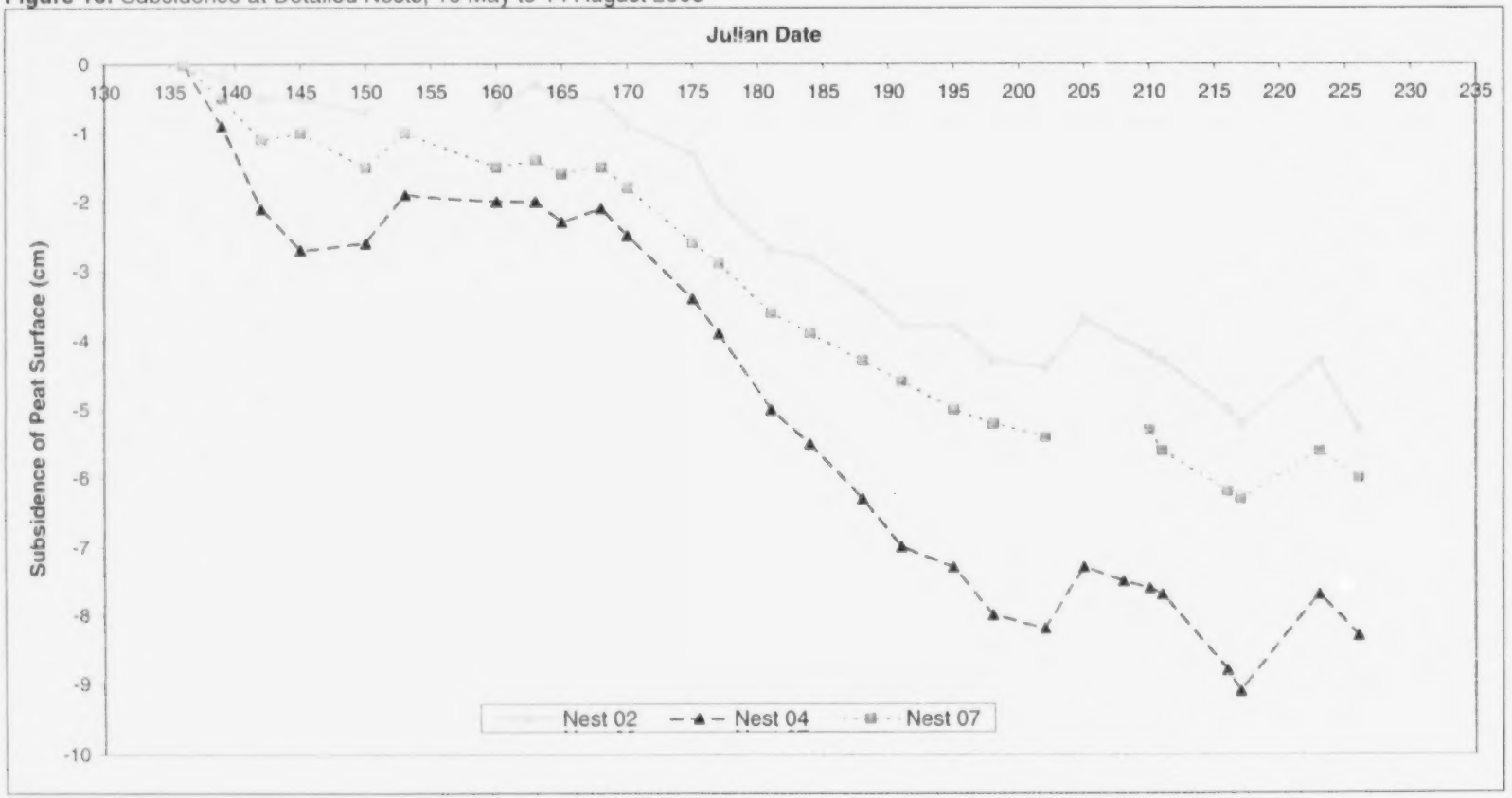
Figure 15: Hydraulic Conductivity by Depth, Field C2



4.3.3 Subsidence and Strain

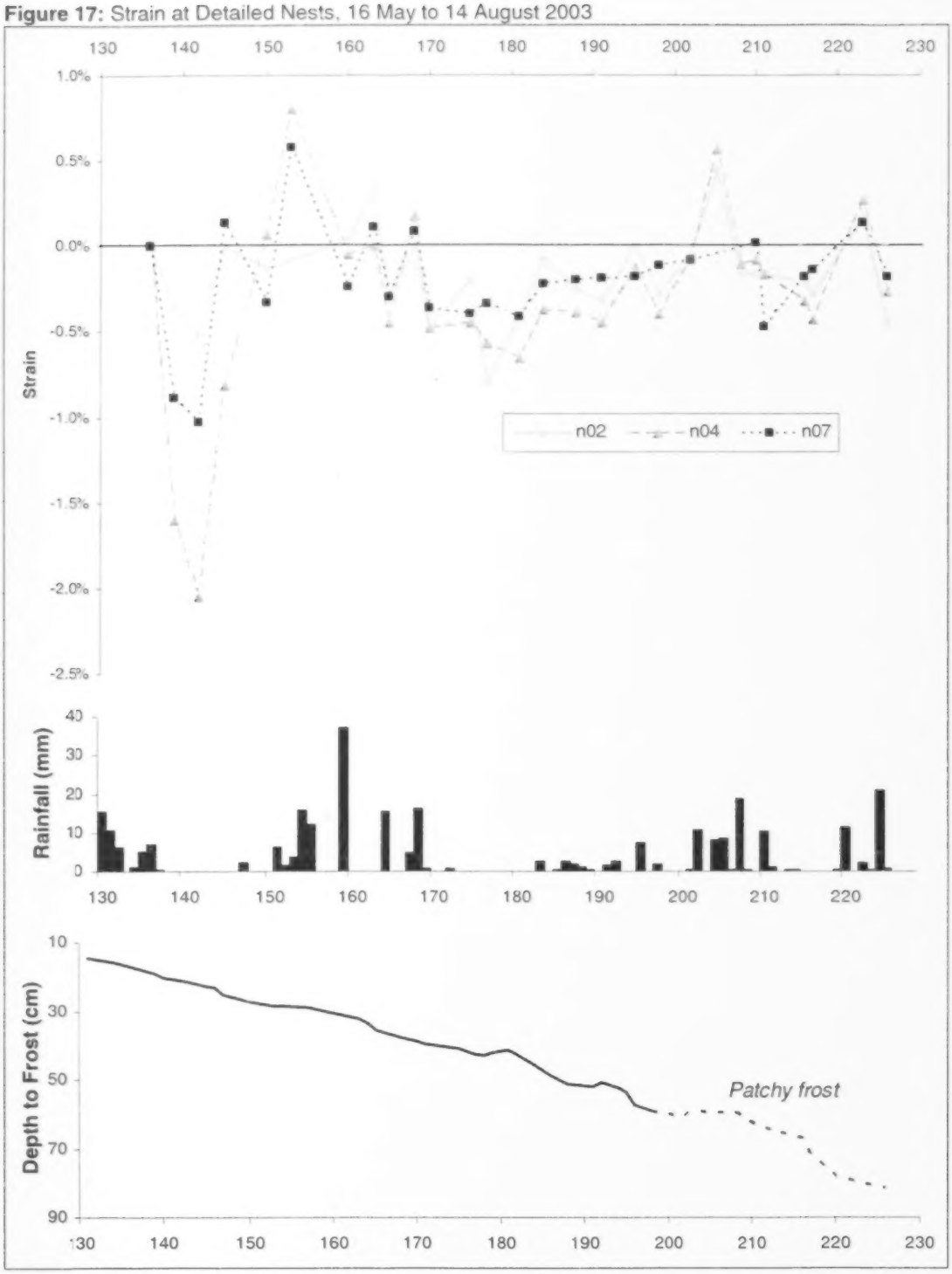
Subsidence was monitored in the harvested area from 16 May to 14 August 2003. Over this three month period, the surface subsided by 5.3 to 8.3 cm (Figure 16). Nest n04 showed the greatest rate of subsidence, while n02 showed the least. Nest n04 is a particularly wet, low-lying site that was flooded during the early spring. Note that there are no subsidence stations in the natural zone for comparison.

Figure 16: Subsidence at Detailed Nests, 16 May to 14 August 2003



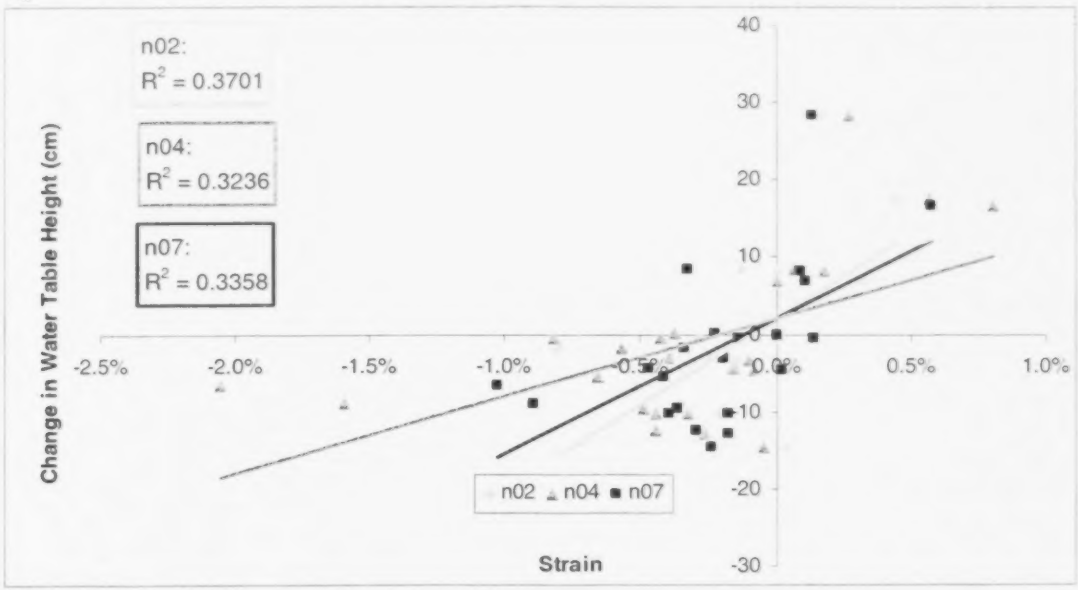
Strain is the relative change in thickness of a layer due to compression and swelling. Since frost remained in the peat for a substantial portion of the summer, the gradual lowering of this frost table changes the thickness of the layer upon which subsidence can occur. Strain provides comparable values on the amount of compression or subsidence occurring during any particular period. Positive strain values indicate expansion of the peat, while negative values indicate compression of the peat. As shown in Figure 17, n04 shows the greatest variability in strain, with values ranging from +0.8% to -2.1%. Both n02 and n07 vary less than n04, with values ranging from +0.6% to -1.0%.

Figure 17: Strain at Detailed Nests, 16 May to 14 August 2003



Although many variables contribute to strain levels within the peat, there is a weak relationship between the water table height and strain (Figure 18) (r^2 values range from 0.32 to 0.37). Figure 18 indicates that an increase in water table causes swelling of the peat, whereas a decrease in the water table causes compression and shrinkage. This swelling and subsidence is also evident in Figure 17.

Figure 18: Strain vs. Water Table, Detailed Nests



4.4 Water Table

4.4.1 Temporal Variability

When data from the automatic water level recorder is plotted for the summer period with daily precipitation values, it is evident that the water table in the harvested zone responds markedly to rainfall events (see Figure 19). In the following figures, the 'natural zone' represents the natural zone transect of piezometers, while 'natural zone base station' indicates n01, which is in the harvested transect line but slightly north of the harvested zone, in a fringe of natural bog (Figure 6).

The harvested area has a much lower water table (with respect to the peat surface) than the natural zone, where the water table is relatively close to the peat surface for the majority of the summer (see Figure 19). However, the natural zone base station has a water table that is similar in height to that found in the harvested zone. With respect to metres above mean sea level, the water table in the natural zone is higher than that in either the harvested zone or the natural zone base station (see Figure 20).

The magnitude of rises and falls in the water table also varies between the harvested zone (AUTO) and natural zone (n01, n08, n09 and n10) (Table 5). During a wet period, the harvested zone water table changes 7.6 times more than in the natural zone. However, during a dry period, the harvested zone water table changes only 1.5 times more than in the natural zone. From a wet to a dry period, the water table in the harvested zone changes 3.2 times more than in the natural zone. Overall, the water table in the harvested zone responds to a greater degree to rainfall events and to evaporation than in the natural zone.

Table 5: Magnitude of Water Table Changes, Harvested Zone vs. Natural Zone

	Magnitude of Rises and Falls (cm)			
Period	**n08**	**n09**	**n10**	**AUTO**
145 to 153 (wet)	4.8	5.0	-1.1	25.0
168 to 181 (dry)	-12.0	-10.0	-10.6	-27.2
153 (wet) to 181 (dry)	-12.6	-10.0	-5.3	-39.0

Figure 19: Water Table Height (cm below peat surface)

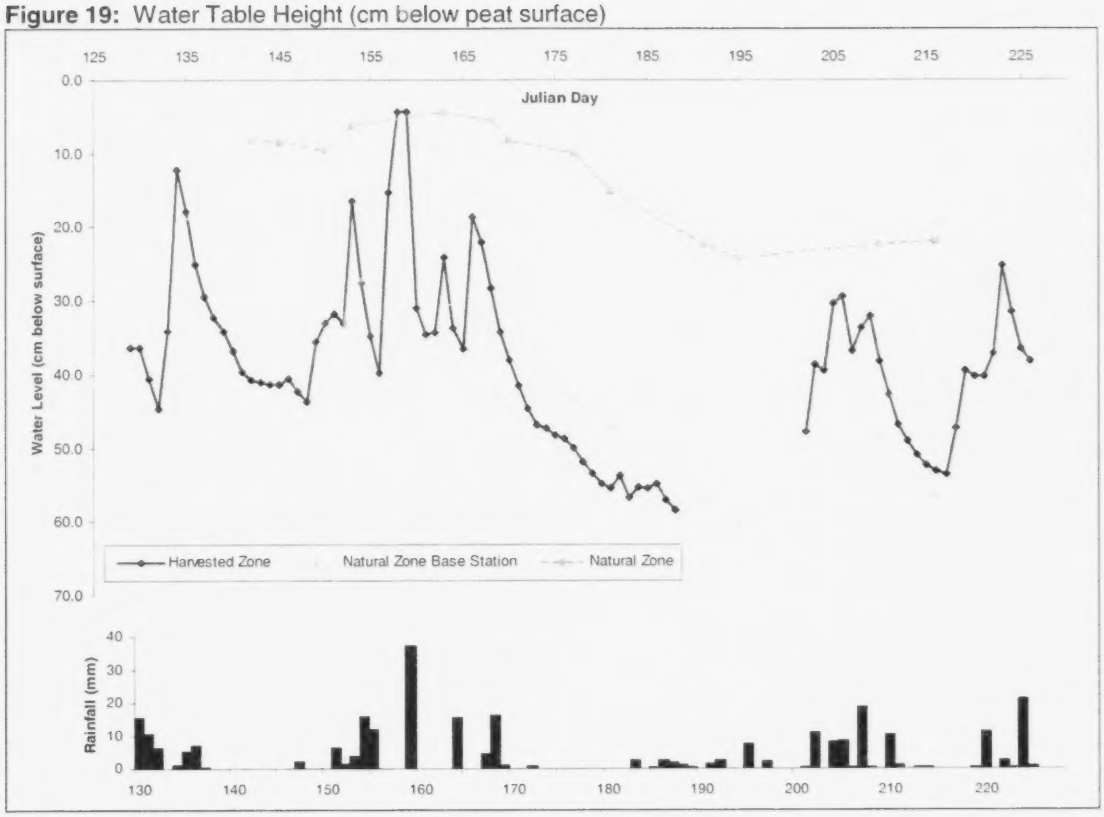
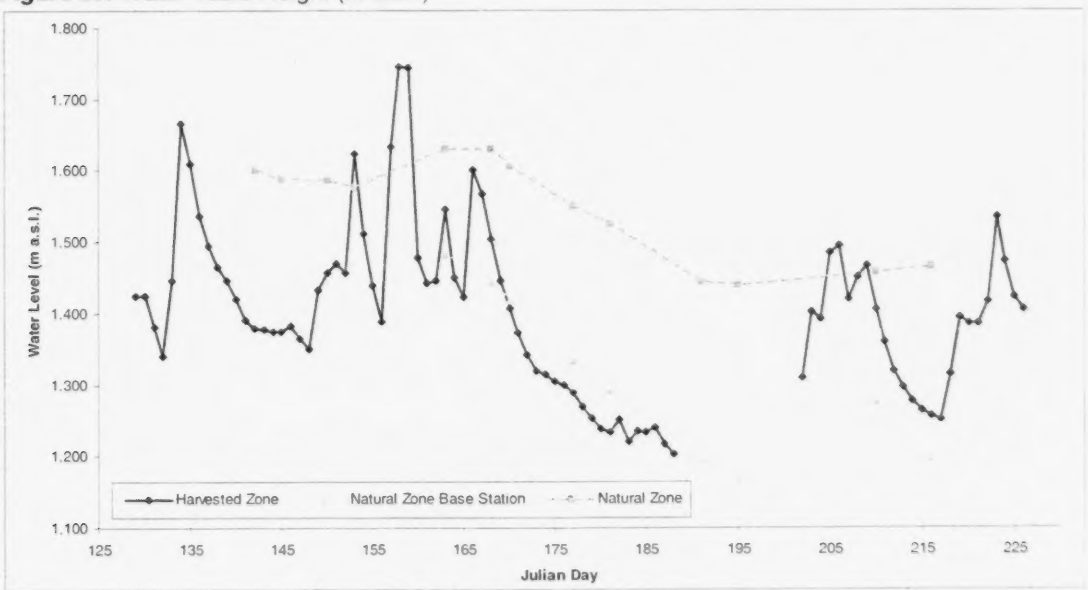


Figure 20: Water Table Height (m a.s.l.)



4.4.2 Surface Water Conditions

The surface water conditions varied throughout the summer, from periods of flooding to periods where there was no surface pooling. As the frost receded, all surface waters disappeared until June 6, when a series of rainstorms caused overflow of the drainage ditches. Seventy millimetres of rain fell between 30 May (Figure 21) and 6 June 2003 (Figure 22), 37 mm of which fell on 6 June. At this date, the frost was within 30 cm of the peat surface. By 9 June 2003 (Figure 23), all the surface water had drained away.

Figure 21: Surface Water Conditions, 30 May 2003

Photo credit: S. Mouneimne

Figure 22: Surface Water Conditions, 6 June 2003

Photo credit: S. Mouneimne

Figure 23: Surface Water Conditions, 9 June 2003

Photo credit: S. Mouneimne

4.5 *Vertical Water Flow*

The array of piezometers at nests allows for an investigation of the vertical water pressure gradient in the peat. A negative gradient indicates a downward flow (more pressure at the surface than at depths), while a positive gradient indicates an upward flow (less pressure at the surface than at depths). Nests in the harvested zone show a minor vertical gradient, while those in the natural zone show a negligible vertical gradient (with the exception of n08) (see Figure 24). The magnitude of the vertical gradient is negligible and ranges from +0.06 to -0.12 (Table 6). Except for n04 and n05, the dry period shows a general downward trend of water movement. During the wet period, n02, n03, n08 and n09 show a downward flow, whereas n01, n04, n05 and n10 show an upward flow. The natural zone transect, since it was fully defrosted for the entire summer, provides data on the vertical flow gradients for thirteen sample days. All nests in the natural zone show a minor but predominantly downward flow of water, despite the presence or absence of precipitation (Table 7).

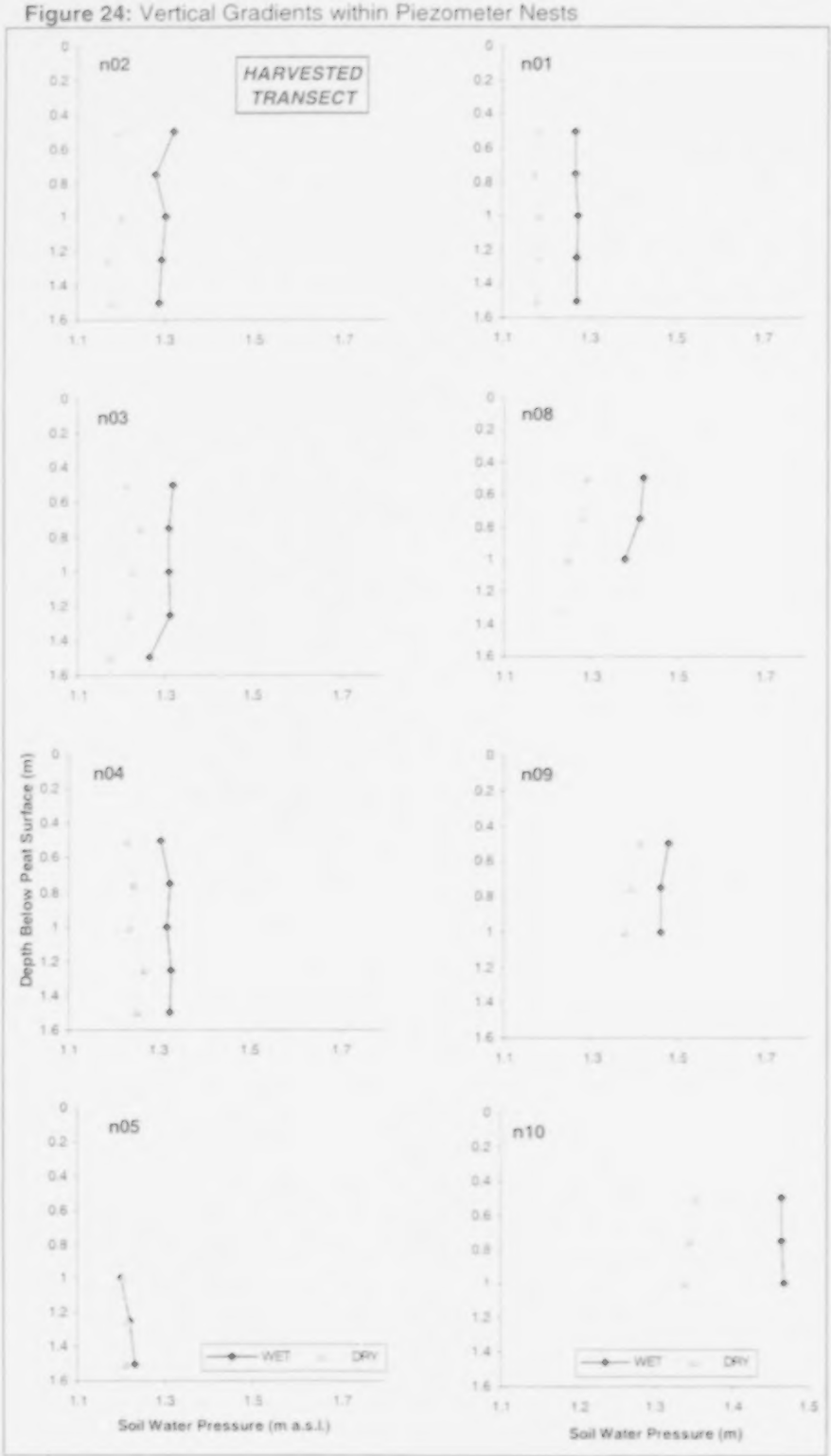
Table 6: Vertical Gradient (from shallow to deep piezometer)

	WET	*DRY*
n01	0.005	-0.003
n02	-0.12	-0.06
n03	-0.05	-0.04
n04	0.02	0.02
n05	0.06	0.01
n08	-0.09	-0.09
n09	-0.03	-0.07
n10	0.006	-0.03

Table 7: Vertical Gradient, All Days, Natural Zone Transect

Nest	*# Days Downward Flow*	*# Days Upward Flow*	*Vertical Gradient Range*
n08	12	0	-0.13 to -0.04
n09	11	2	-0.14 to +0.03
n10	9	4	-0.07 to +0.02

Figure 24: Vertical Gradients within Piezometer Nests



4.6 *Pore Water Pressure*

Pore water pressure was measured by arrays of tensiometers placed in the three detailed nests, at depths of 2, 5, 10, 20 and 30 cm from the peat surface. No vertical gradient is evident, other than between the 2 cm and 5 cm tensiometers. The magnitude of this surface pore water pressure varies for each nest of piezometers; it also varies based on periods of evaporation or precipitation (Table 8). A negative gradient indicates that water flows downwards (higher pressure at surface), whereas a positive gradient indicates that water flows upwards (lower pressure at surface).

Table 8: Variability of Vertical Pore Water Pressure Gradient, 2 to 5 cm, 2003

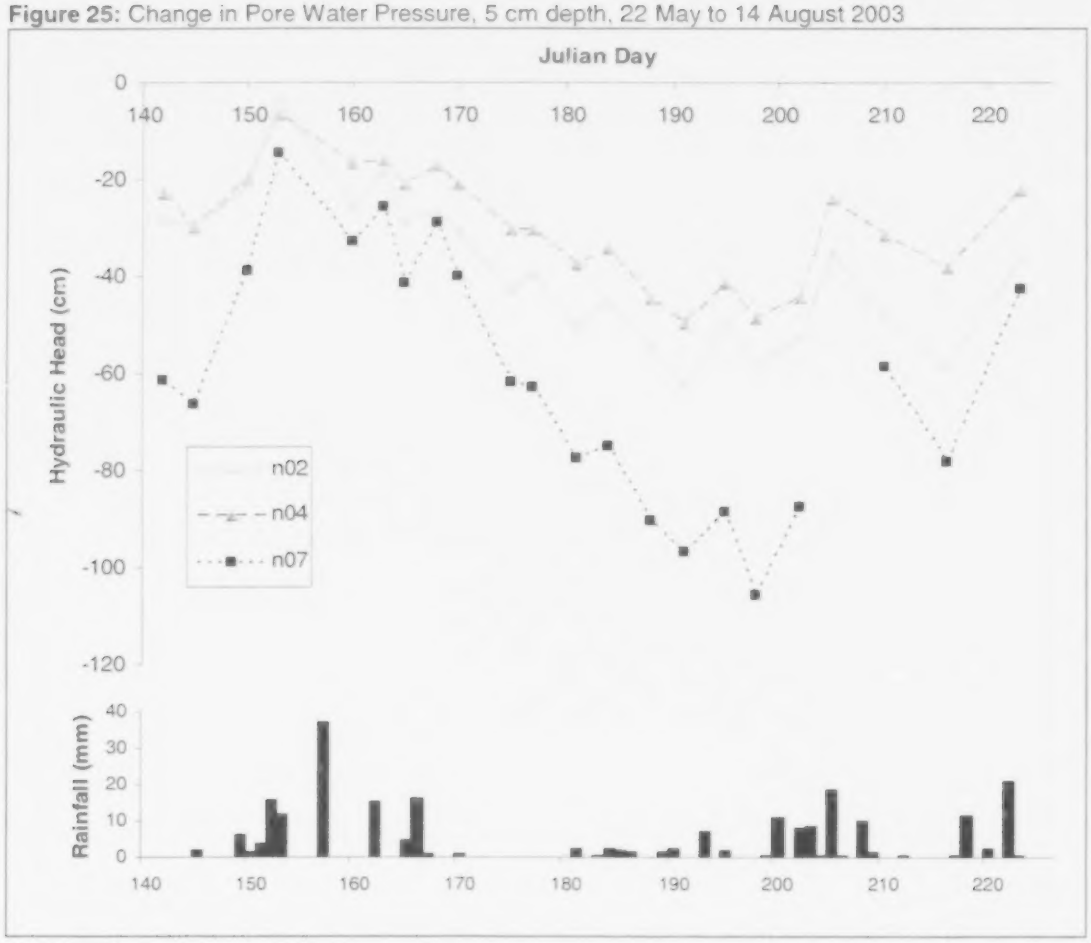
Nest	*Vertical Gradient (cm)*
n02	-0.3 to +1.7
n04	+0.3 to +1.3
n07	-1.3 to +3.7

Figure 25 shows the pore water pressure for the 5 cm tensiometer for the entire summer period. The wettest site, n04, has the highest pressure, whereas n07, the driest site, has a much lower pore water pressure. Table 9 shows that n07 responds to precipitation and evaporation events with a change in pressure that is two times greater than the response at n02 or n04.

Table 9: Magnitude of Pore Water Pressure Changes (at 5 cm)

	Period (Julian Days) *(Values are in cm of pressure)*		
Site	Wet (145 to 153)	Dry (168 to 181)	**Site Description**
n02	27	-24	moderately dry
n04	23	-20	wet
n07	52	-48	dry

Figure 25: Change in Pore Water Pressure, 5 cm depth, 22 May to 14 August 2003



4.7 Salinity

Although salinity values will be used for all variables presented below, there is a strong correlation between salinity and chloride concentrations (r^2 = 0.9894) and salinity and electrical conductivity (r^2 = 0.9982). The graphs and conversion equations are included as Appendix K.

4.7.1 Temporal Variability of Salinity and pH

Figure 26 shows the variability of salinity concentrations over the summer season in the harvested transect (nests n02, n03 and n04). Table 10 summarizes the precipitation events and the number of days of precipitation that occur between measurement days. Nest n02 is a relatively dry site, while n03 and n04 are relatively wet, seasonally flooded sites. Salinity

in the surface layer (4 cm from the peat surface) rises by a greater magnitude than the deeper layers during a relatively dry period of the summer (see Table 11).

Figure 26: Salinity in the Surface Peat Layers, 3 June to 5 August 2003

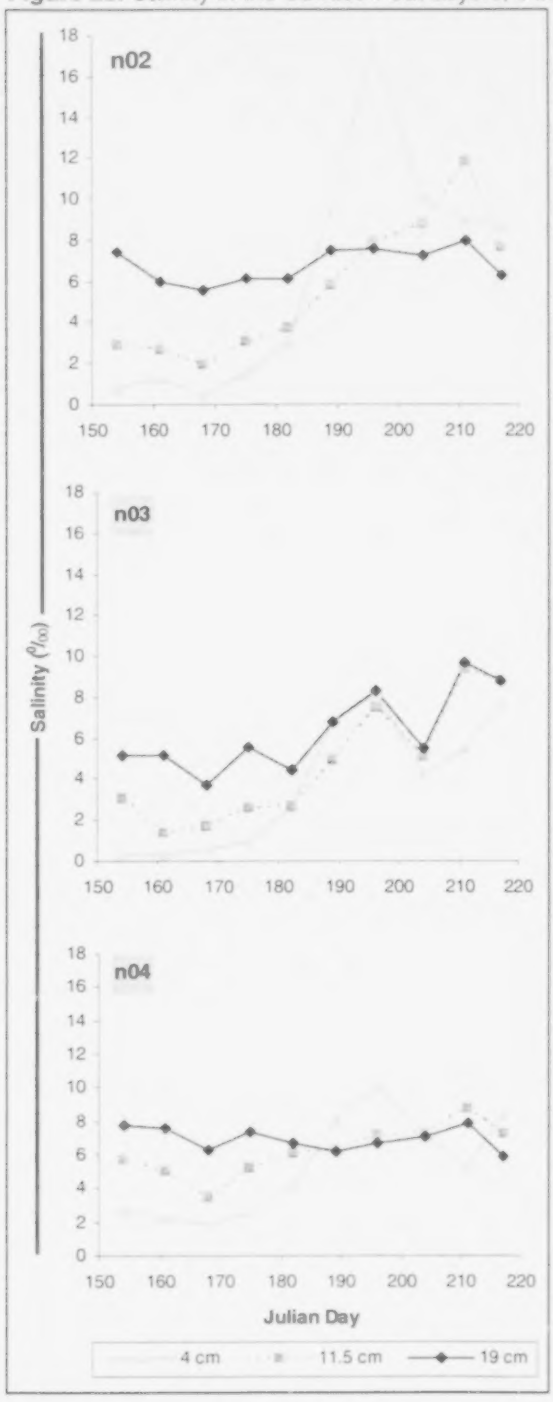


Table 10: Precipitation Events between Surface Peat Salinity Measurements

Julian Day		
154 to 161	37.1 mm	(1 day)
162 to 168	37.3 mm	(5 days)
169 to 175	0.8 mm	(1 day)
176 to 182	2.8 mm	(3 days)
183 to 189	7.6 mm	(6 days)
190 to 196	11.7 mm	(3 days)
197 to 204	27.9 mm	(5 days)
205 to 211	30.8 mm	(5 days)
212 to 217	1.0 mm	(3 days)

Table 11: Change in Peat Surface Salinity from Day 168 to Day 196

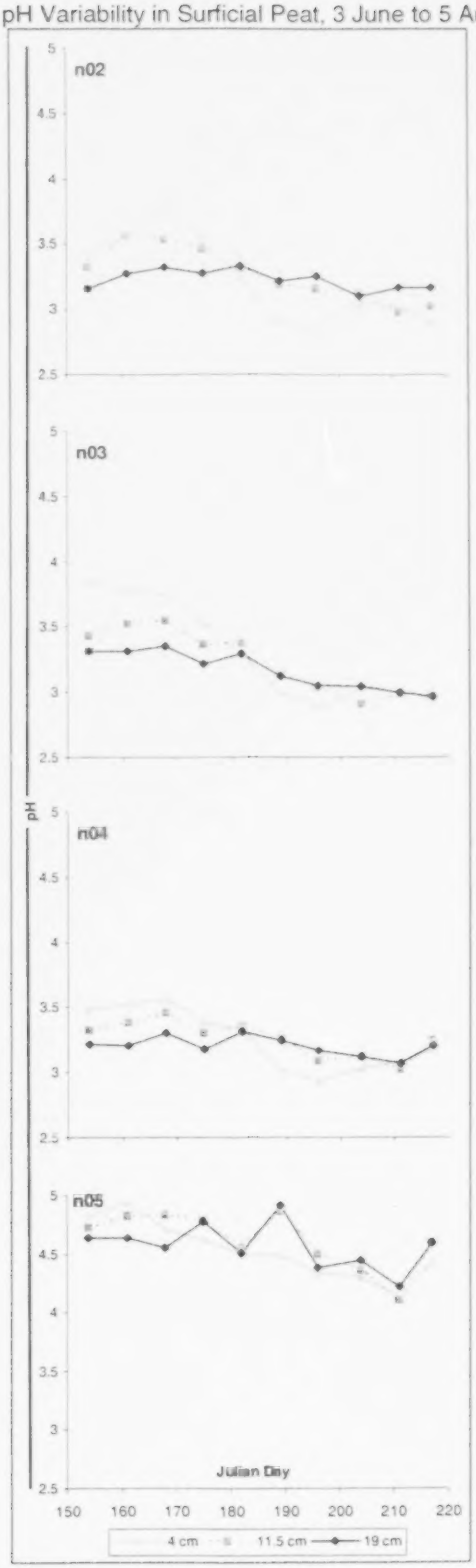
Nest	4 cm depth		11.5 cm depth		19 cm depth	
	change (‰)	%	*change (‰)*	%	*change (‰)*	%
n02	17.0	4250%	6.0	316%	2.0	36%
n03	7.7	1283%	5.8	341%	4.6	124%
n04	8.2	432%	3.8	112%	0.4	6%
n05	0.1	100%	0.0	0%	0.0	0%
n06	0.5	500%	-0.1	-100%	0.0	0%
n07	0.1	100%	0.0	0%	0.0	0%

Similar to salinity, pH values also show a spatial and temporal variability over the summer seasons (see Figure 27). While salinity rises during dry periods, pH values drop. Overall, the surface peat layers become more acidic over the summer, with a greater change observed at the surface layer (4 cm from peat surface) than at the deeper layers (Table 12).

Table 12: Change in pH in the Peat Surface from Day 168 to Day 196

Nest	4 cm layer		11.5 cm layer		19 cm layer	
	change	%	*change*	%	*change*	%
n02	-0.98	-26%	-0.37	-10%	-0.07	-2%
n03	-0.86	-23%	-0.51	-14%	-0.30	-9%
n04	-0.63	-18%	-0.37	-11%	-0.13	-4%
n05	-0.38	-8%	-0.33	-7%	-0.17	-4%

Figure 27: pH Variability in Surficial Peat, 3 June to 5 August 2003

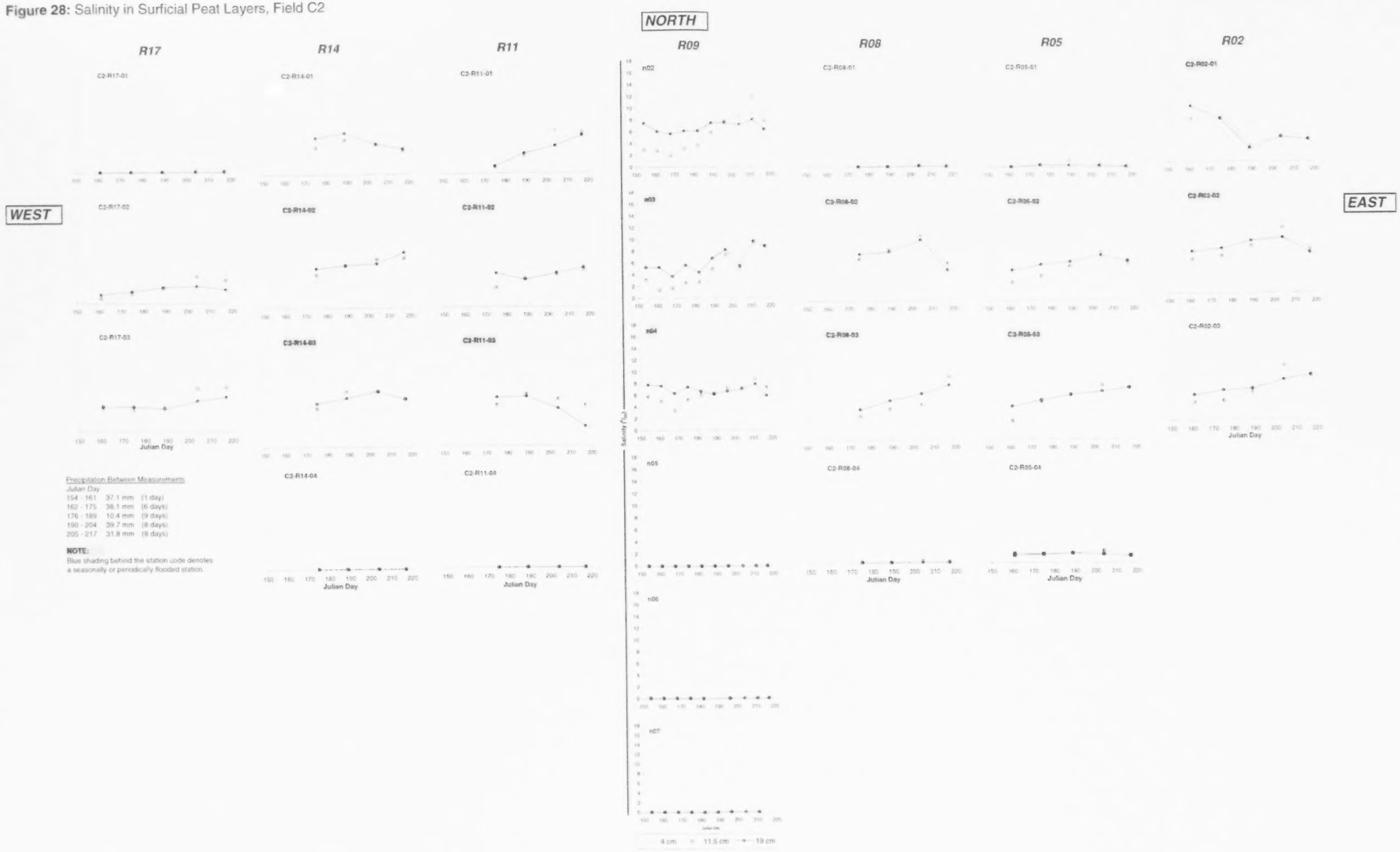


4.7.2 Spatial Variability

Figure 28 shows the salinity concentrations for all 22 sampling stations in field C2, as well as the six nests in the harvested transect. All graphs are aligned as they occur in space, as seen in Figure 9. The stations are numbered in the following format: field code – row number – station number (e.g. C2–R08–01). Stations are numbered from north to south. Note that the blue (grey) shading on the station code denotes a station that is periodically or seasonally flooded. These flooded areas are typically at lower elevations, and are generally correlated with the central areas of each row (station numbers 02 and 03). Figure 28 also shows precipitation totals and the number of precipitation days between each measurement period.

There is a weak relationship between elevation and salinity, as seen in Figure 29, which shows that lower elevations have a higher salinity. There is also a weak relationship ($r^2 = 0.2679$) between elevation and the change in salinity from 24 Jun to 8 Jul 2003. This period was relatively dry, with only 10.4 mm of rain in 14 days. Although the relationship is weak, it indicates that the salinity of peat at lower elevations increased more than the salinity of peat at higher elevations.

Figure 28: Salinity in Surficial Peat Layers, Field C2

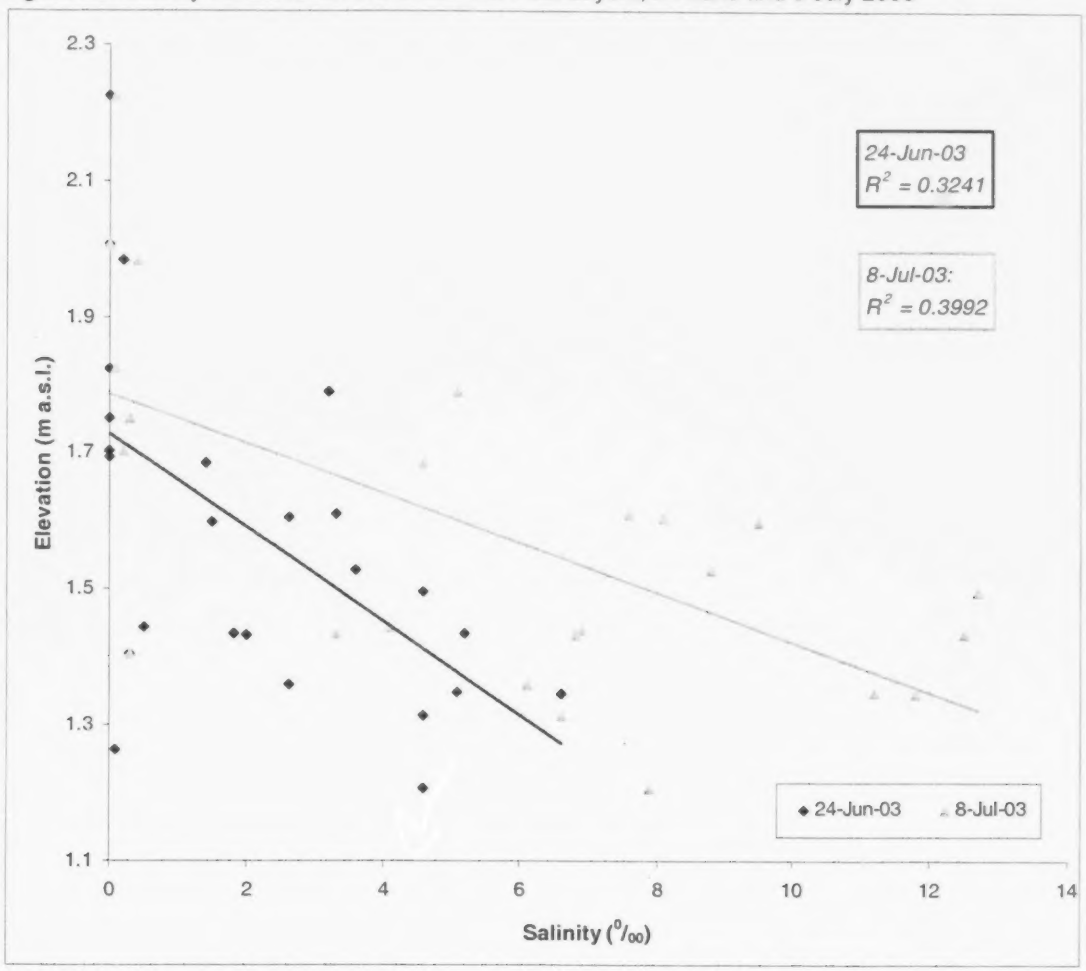


Precipitation Between Measurements

Julian Day		
154 - 161	37.1 mm	(1 day)
162 - 175	38.1 mm	(6 days)
176 - 189	10.4 mm	(9 days)
190 - 204	39.7 mm	(8 days)
205 - 217	31.8 mm	(8 days)

NOTE:
Blue shading behind the station code denotes a seasonally or periodically flooded station.

Figure 29: Salinity vs. Elevation in the Surficial Peat Layers, 24 June and 8 July 2003



4.7.3 Vertical Distribution

Deep Cores

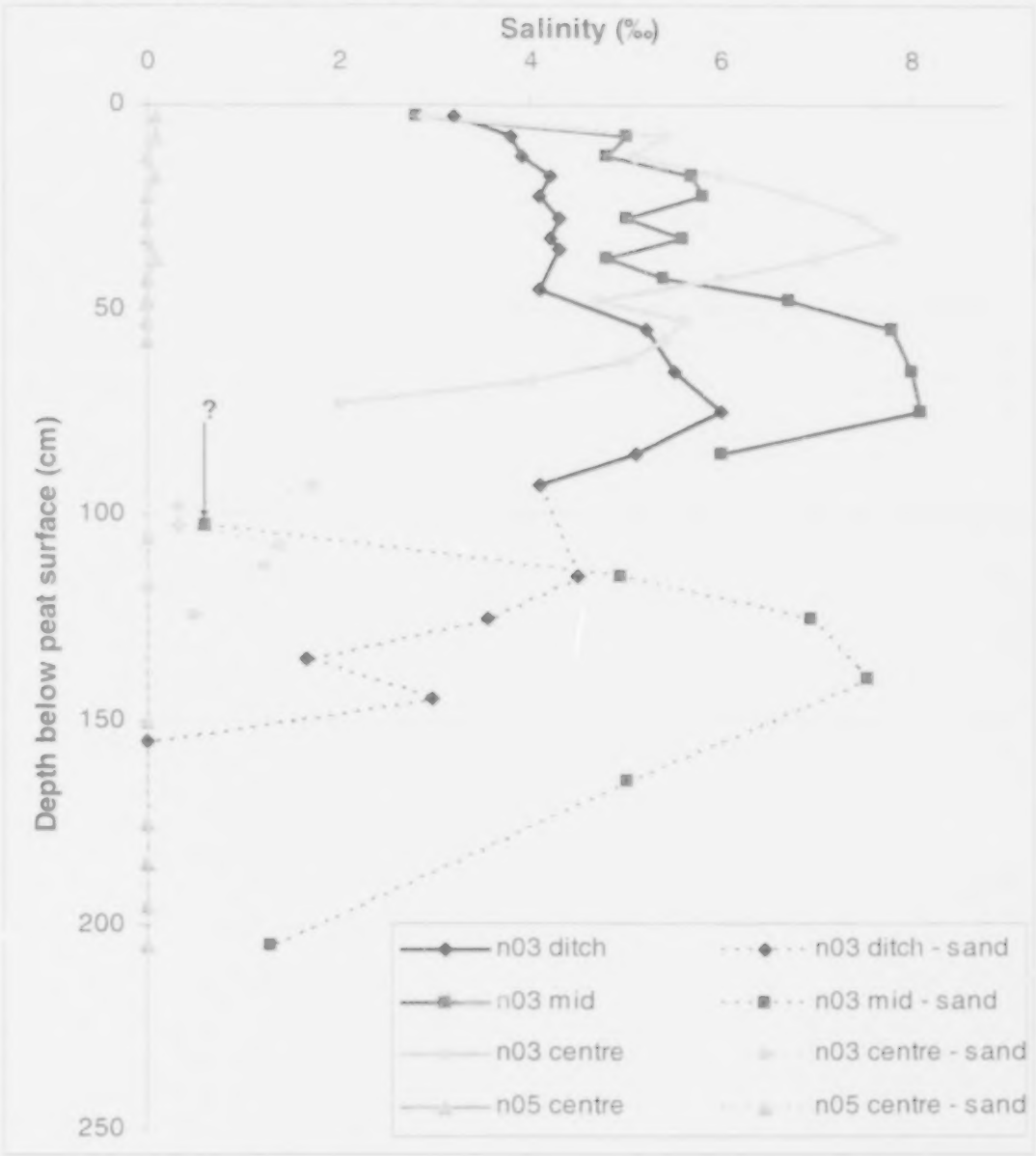
The vertical distribution of salinity was examined in detail in four peat cores (see Figure 30). Nest n05 was known to have no salinity at the surface (see Figure 28), and hence this core was taken as a comparison to determine if salinity increased with depth. Such is not the case, as salinity at n05 never rose above 0.1‰. Nest n03, however, was known to have high levels of surface salinity (see Figure 28). Three cores were taken to examine the effect of the drainage ditch upon salinity levels at depths in the peat. The 'ditch' core was taken immediately adjacent to the ditch, the 'mid' core was taken approximately 10 metres from the ditch, and the 'centre' core was taken in the centre of the field, approximately 15 m from the ditch. The centre core is on a slightly higher elevation than the mid or ditch cores. It should also be noted that this section of ditch frequently overflows and floods the area from which the ditch and mid cores were taken. The centre core is generally above the flooding level. This data has not been corrected for surface elevation. All depth values are shown in relation to the peat surface. The top of the sand layer for the n03 'mid' core occurs at approximately 0.6 m a.s.l..

With respect to salinity values for the peat layers, salinity in the centre core peaked at 7.8‰, at 32.5 cm from the surface. Salinity in the mid and ditch cores, however, peaked much deeper than in the centre core, at 75 cm from the surface. The mid core demonstrated much higher salinity levels than the ditch core, with peak salinity values of 8.1‰ and 6.0‰, respectively.

Salinity values in the sand layers below the peat (denoted by the dashed lines) must be interpreted with some degree of scepticism due to assumptions made during the calculations of these values (see section 3.2.5, Deep Peat Cores). The values generally continue to decrease with depth, with the exception of the mid core. Nest n05 does not

show any salinity in the sand layer, unlike all three cores at n03, which show salinity values as high as 7.5‰.

Figure 30: Salinity in Peat Cores, n03 and n05



Piezometers

Figure 31 shows the mean, maximum and minimum salinity of water entering the piezometers for the summer season. The salinity values have been averaged over the summer since it was found that the values were not highly variable. Table 13 and Table 14 show the number of samples that are included in the mean value. Note that not all nests and piezometers have been included in this analysis, often because many piezometers were frozen for most of the summer.

In general, salinity decreases with depth in the harvested zone nests, while it increases with depth in the natural zone nests. The exception is n02, with a relatively high salinity value recorded in the deep piezometer, which is recording salinity values for the sand layer below the peat. Peak salinities in the natural site range from 0.4‰ (n01) to 3.9‰ (n08), while they vary from 1.6‰ (n02) to 3.5‰ (n03) in the harvested zone.

Figure 31: Salinity in Piezometer Water, Summer 2003

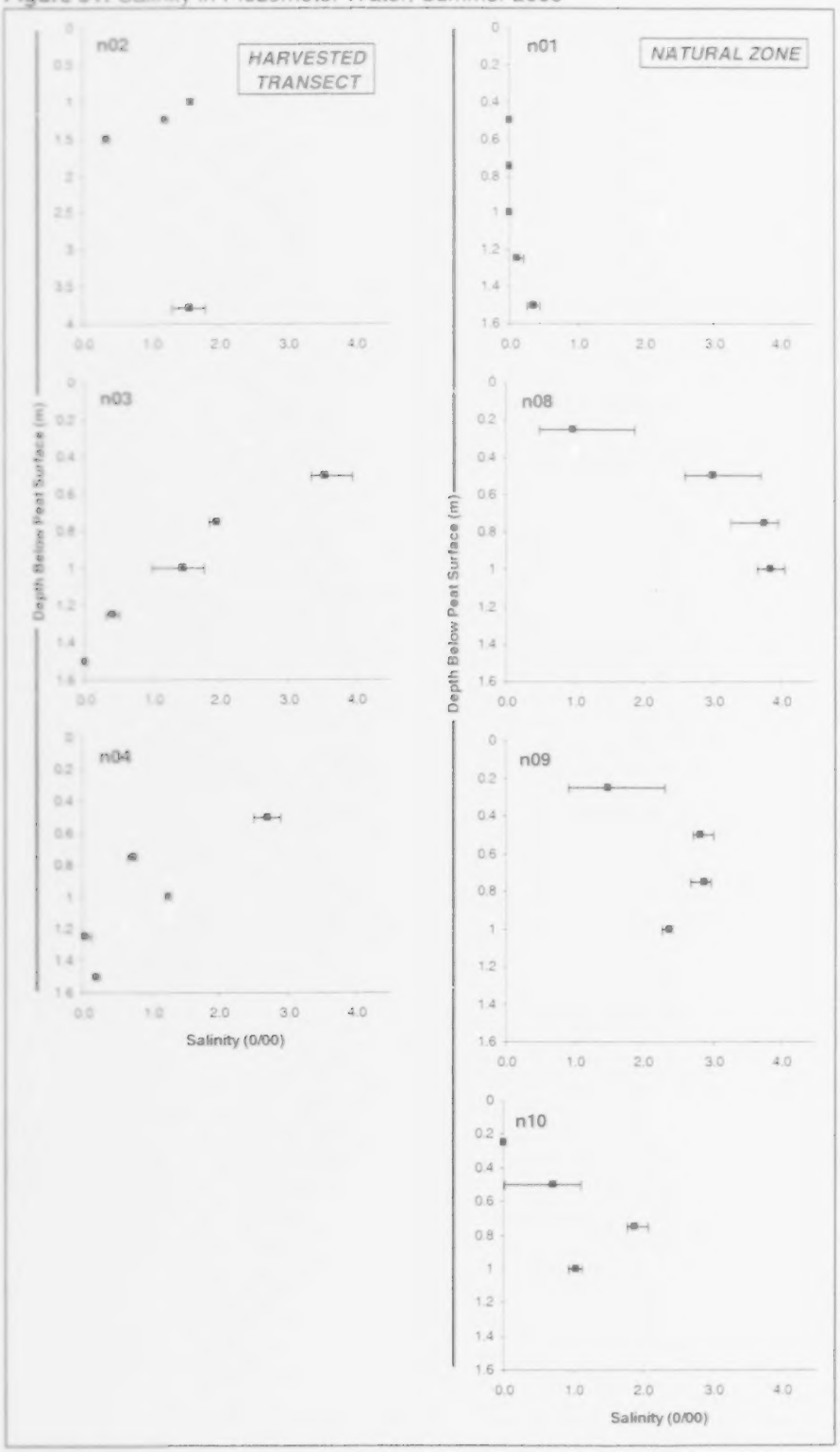


Table 13: Number of Samples in Calculated Mean Salinity, Natural Zone

Nest	*Depth (cm)*	*Number of samples*
n01	150	7
	125	7
	100	7
	75	7
	50	2
n08	100	7
	75	7
	50	7
	25	4
n09	100	7
	75	7
	50	7
	25	5
n10	100	3
	75	7
	50	7
	25	5

Table 14: Number of Samples in Calculated Mean Salinity, Harvested Zone

Nest	*Depth (cm)*	*Number of samples*
n02	150	2
	125	1
	100	1
	Deep	5
n03	150	2
	125	7
	100	7
	75	2
	50	3
n04	150	2
	125	3
	100	2
	75	2
	50	2

5.0 DISCUSSION

5.1 Comparison of Vertical Salinity Values

Salinity of water sampled from the piezometers (Figure 31) and from vertical salinity cores (Figure 30) at n03 are possibly inconsistent. The 50 cm piezometer, with slotted intake open between 42.5 and 57.5 cm, had a mean summer salinity of 3.5‰. Water sampled from the 'mid' core obtained between 45 and 60 cm had a salinity of 6.7 to 7.8‰. Futhermore, at the 75 cm depth the piezometer water was approximately 2.0‰ (slotted intake open between 67.5 to 82.5 cm), whereas the core salinity ranged from 8.0 at 65 cm, to 8.1‰ at 75 cm, to 6.0‰ at 85 cm depth. The piezometers and the core sampling location were approximately 1 to 2 m apart. The sampling depths are possibly slightly confounded because the surface from which the cores were extracted experienced subsidence before the cores were obtained in July.

No satisfactory explanation could be found to explain the difference between observed vertical salinity values. However, both methods (piezometers and core) indicate that the source of solutes is from the surface, consistent with inundation of saltwater during the storm surge of 21 January 2000.

5.2 Vertical and Horizontal Flows of Water

All piezometers within the natural zone transect show a predominant downward flow of water, despite periods of precipitation or extended dryness (Table 7). This predominant downward flow indicates that surface water is being recharged. There is also a horizontal gradient driving flow from n10 towards n08, northwards towards the ocean.

The harvested zone transect has less data because many piezometers were frozen for most of the summer (see Appendix H). The presence of the frost may affect both the horizontal and vertical flow of water, and its role should be monitored in future field seasons. The magnitude of horizontal flow is uncertain, since wells in the harvested zone were also

frozen. However, water pressures measured in piezometers indicate that horizontal gradients are negligible (Figure 24).

With regards to vertical flow in the upper layer of peat at the detailed nests (n02, n04 and n07), all tensiometers show an upward flow of water during periods of higher evaporative losses, and a downward flow of water during periods of precipitation (also see Price, 1994; Wilcox, 1986; Price and Woo, 1988). However, n04 allows for a comparison of three sample dates during which both tensiometer and piezometer data are available. During a wet period (Julian days 210 to 211), the tensiometers indicate a downward flow, while the piezometers show an upward flow. During this period, the salinity of the surface peat declines, suggesting leaching of solutes away from the surface. The upward flow indicated by the piezometers is consistent over the season, but during a dry period (Julian days 216 to 217) both the tensiometers and the piezometers indicate an upward flow of water, while a concurrent rise in surface salinity also suggests concentration of solutes in the surface peat. The only downward flow observed in the n04 piezometers occurred after a 21 mm rainfall event (Julian day 222).

5.3 Vertical and Horizontal Patterns and Fluxes of Salt

The general occurrence of salts corresponds to lower areas (Figure 28) that would have been inundated with seawater during the storm surge. More elevated areas may have escaped inundation, or may have drained as the surge abated, allowing little saltwater to enter the frozen soil. Following retreat of the flood waters, the more drained areas experience greater leaching, thus lowering salinity. Flooded depressions, where salt loading was greater, undergo less leaching due to a higher water table, and the higher evaporation rates of wetter soils promote accumulation of salt from the evaporating surface.

Site conditions have changed since the storm surge. Initially, drainage was maintained (by pumping), so leaching and the downward migration of salts may have occurred throughout the site. Subsequently, drainage (pumping) was abandoned, and thus

leaching became limited to low-lying flooded or wet areas. These correspond to the areas of higher salinity. Currently, changes in salinity near the surface are related to the mobility of salt in the vertical profile. The vertical distribution of salt (see Figure 30) therefore reflects its net transport since loading occurred. Most of the solutes are in the upper 75 cm of the peat profile (Figure 30), and decrease sharply below 75 cm. The downward hydraulic gradients measured in the unsaturated zone suggest downward leaching of solute. If the (upward) piezometric gradients in the saturated zone are really occurring, it is unlikely that solute would penetrate much further. An alternate mechanism, however, may result from the freeze-out of solutes during the winter period (Marion, 1995), which would cause a downward flux of solute as the frost table descended. Downward density-drive solute flux could enhance this.

While the salinity decreases sharply below 75 cm, there are intermediate levels of salinity in the sand layers underlying the peat, although the level of this salinity varies at all three profile sites (the reliability of this data is discussed in section 5.1). The salt in these sand layers could be relict (Price and Woo, 1988), or could result from the rise of the saltwater-freshwater interface. Since salinity in the sand underlying the n05 core is very low, it is unlikely that fossil salts occur in the mineral substrate. The decrease in hydraulic head caused by drainage during peat mining operations may have caused a rise of the freshwater-saltwater boundary (Atkinson *et al.*, 1986). Future research efforts should include testing of the hydraulic conductivity of the sand layers below the peat to determine the potential for vertical flow across the sand-peat interface.

The temporal variability in surface peat salinity (Figure 26) indicates the influence of concentration from evaporation and dilution from precipitation. However, the relative roles of advection and diffusion have not been evaluated. Given that peak salinities were observed at approximately 75 cm for the 'mid' and 'ditch' n03 profiles, and that Wilcox (1986) found that diffusion accounted for only 2.5% of the predicted movement of solutes

through the peat soil (and thus he concluded that advection was the major transport mechanism for solutes), it seems unlikely that diffusion (leaching) is the major transport mechanism for solutes at Pokesudie. More detailed measurement of the vertical water flux, as well as the role of cryogenic processes, should be evaluated in future research efforts to determine the relative roles of the various possible transport mechanisms.

6.0 CONCLUSIONS

Despite inconsistencies between the piezometer and core derived vertical salinity profiles, both methods demonstrate that the source of solutes is from the surface. Although saltwater intrusion cannot be ruled out, the major source of solutes has been indicated to be the storm surge of 21 January 2000. In addition, it is unlikely that salinity observed in the sand substrate is a result of relict salts deposited prior to development of the peat. Further research is required to determine the permeability of this underlying sand and the potential for flow across the sand/peat boundary.

There is a marked concentration of salts in the lower-lying areas of the harvested bog. These areas were likely exposed to greater inundation during the storm surge than were areas of a higher elevation. In addition, the higher water table in these flooded areas results in less vertical leaching of solutes and a higher rate of evaporation, both of which contribute to relatively high salinity levels.

Water in the natural zone transect flows towards the ocean, and there is a recharge of surface water in these areas. Although frozen piezometers and wells prevent a similar conclusion from being drawn for the harvested zone, both tensiometers and surface peat water samples indicate that periods of evaporation cause concentration of solutes at the surface, while periods of precipitation cause leaching of solutes from the surface. The presence of ground frost may be affecting the vertical movement of water and solutes, and the freezing process may also cause a downward flux of solutes as the freezing front descends in the peat profile. Further research is required to monitor and evaluate the relative roles of cryogenic processes, snowmelt, advection and diffusion in the transport of solutes at the Pokesudie cutover bog.

7.0 RECOMMENDATIONS

The following recommendations highlight possible research directions for studying saltwater contamination on the Pokesudie cutover bog.

- *That the relative roles of precipitation, evaporation, snowmelt and freezing be evaluated as transport mechanisms*
  - ✓ Take additional cores at n03, at the beginning of May (if possible), to compare the vertical salinity profile with that observed in July 2003
  - ✓ Monitor evaporation to quantify its relation to changes in salinity
  - ✓ Monitor salinity above and below the frost, or during movement of the freezing front
  - ✓ Determine if the frost layer acts as an impermeable boundary, or if water (and solutes) can flow through it
- *That there be an evaluation of possible flow across or along the sand/peat interface*
  - ✓ Determine permeability of sand substrate
- *That the water flow and the variability of salinity be determined in relation to the ditches*
- *That the spatial variability of salinity be monitored over a relatively small area to determine the importance of spatial variability with respect to observed trends*

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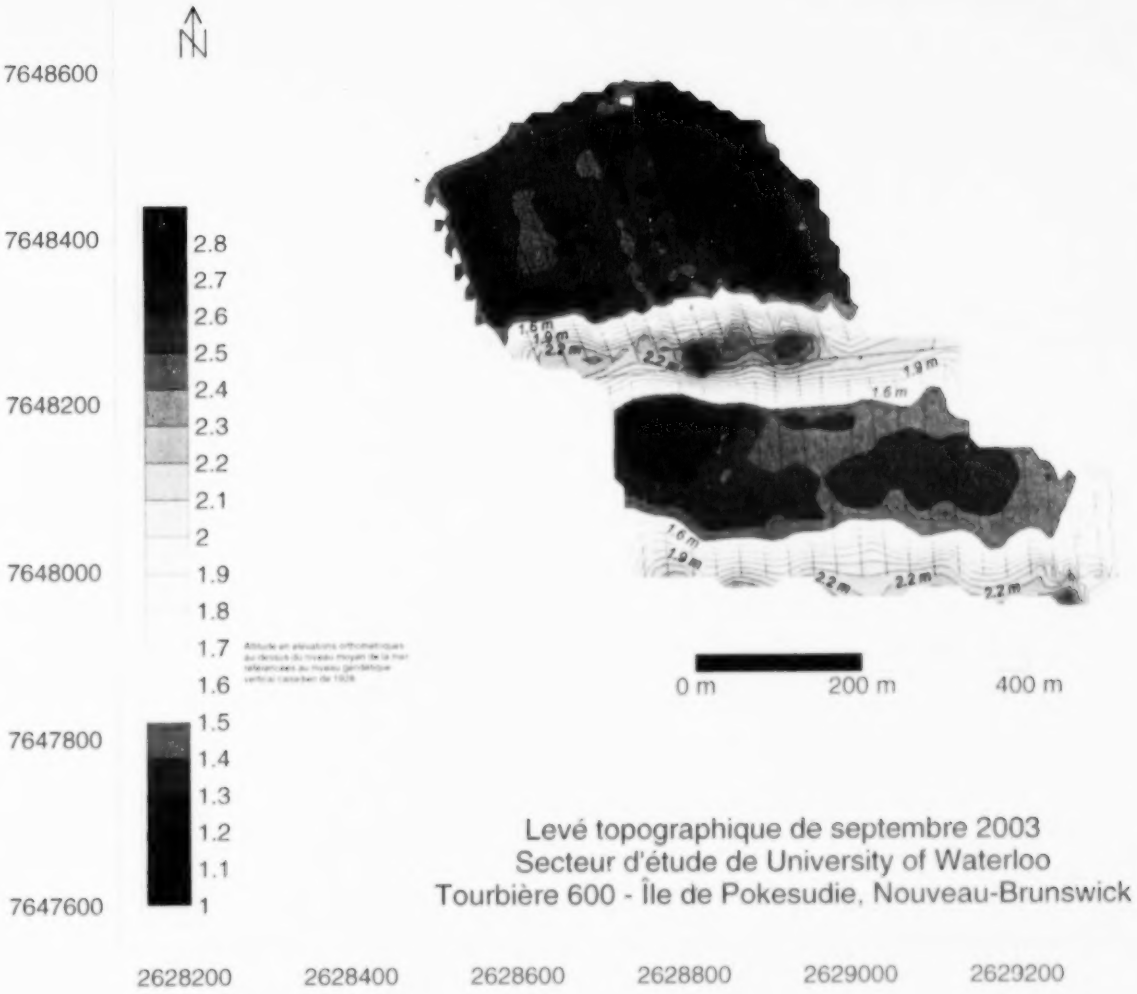
APPENDICES

APPENDIX A: POKESUDIE TOPOGRAPHY

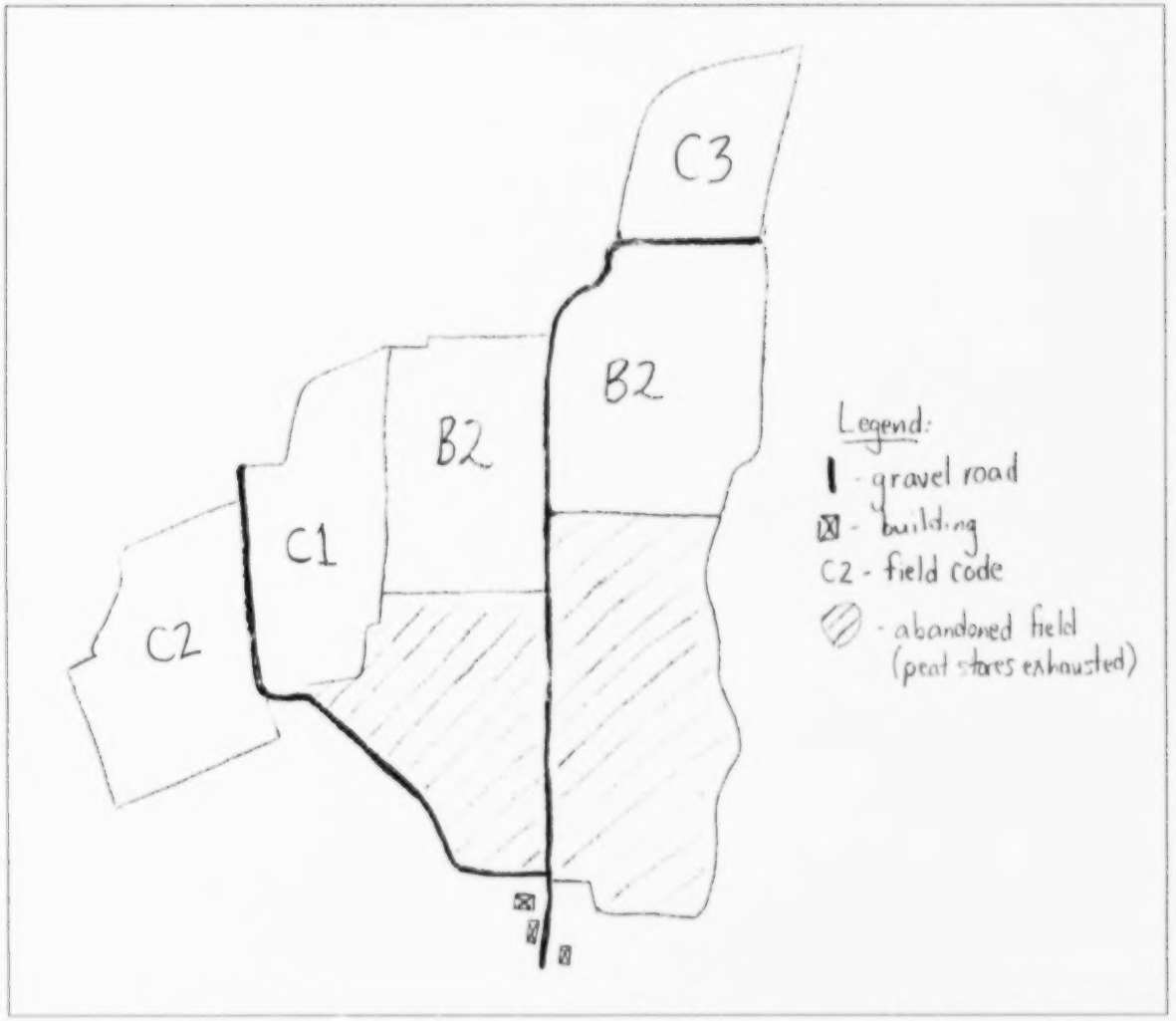
Levé topographique - Tourbière 600 - Île de Pokesudie
Données topographiques : Burton Cain, a.g. N.-B. (2003)
Cartographie : Jacques Thibault, géosc., (2004)
Ministère des Ressources naturelles du Nouveau-Brunswick
7648500
7648000
7647500
7647000
7646500
2627500
2628000
2628500
2629000
2629500
2630000
2630500
2631000
4.00 m
3.75 m
3.50 m
3.25 m
3.00 m
2.75 m
2.50 m
2.25 m
2.00 m
1.75 m
1.50 m
1.25 m
1.00 m
0.75 m
0.50 m
0.25 m
0.00 m
Altitude en élevations orthometriques au dessus du niveau moyen de la mer référencées au niveau géodetique vertical canadien de 1928
0.00 m
500.00 m
1000.00 m

Levé topographique de septembre 2003
Secteur d'étude de University of Waterloo
Tourbière 600 - Île de Pokesudie, Nouveau-Brunswick



Levé topographique de septembre 2003
Secteur d'étude de University of Waterloo
Tourbière 600 - Île de Pokesudie, Nouveau-Brunswick

APPENDIX B: POKESUDIE FIELD CODES



APPENDIX C: INSTRUMENT SPECIFICATIONS

Instrument Name	Operational Limit(s)	Variable Measured	Measurement Range	Resolution	Accuracy
Temperature Probes 107 and 107B	-35° to +50°C	Air and soil temperature (°C)	-35° to +50°C	0.01°C	+/- 0.2°C (from 0° to 50°C) +/- 0.4°C (from -35° to 0°C)
Conductivity and Temperature Probe CS547A (A547 Interface)	3.0 to 9.0 pH 0° to 50°C	Electrical conductivity (mS)	0.005 to 7.0 mS cm^{-1}	0.001 mS	+/- 5%: 0.44 to 7.0 mS cm^{-1} +/- 10%: 0.005 to 0.44 mS cm^{-1}
		Water temperature (°C)	0° to 50°C	0.1°C	+/- 0.4°C
Conductivity Handheld Meter (LF 330) with Standard Conductivity Cell – TetraCon 325	-10° to +55°C	Electrical conductivity (µS and mS)	0 to 500 mS cm^{-1}	0.001 µS cm^{-1} (0-1.999 µS cm^{-1}) 0.01 µS cm^{-1} (0-19.99 µS cm^{-1}) 0.1 µS cm^{-1} (0-199.9 µS cm^{-1}) 1.0 µS cm^{-1} (0-1999 µS cm^{-1}) 0.01 mS cm^{-1} (0-19.99 mS cm^{-1}) 0.1 mS cm^{-1} (0-199.9 µS cm^{-1}) 1 mS cm^{-1} (0-500 µS cm^{-1})	+/- 1% of measured value +/- 1 digit
		Salinity (‰)	0.0 to 70.0 ‰	0.01 ‰	+/- 0.1 ‰ (0.0 to 42.0 ‰ with 5° to 25°C) +/- 0.2 ‰ (0.0 to 42.0 ‰ with 25° to 30°C)
		Temperature (°C)	-5° to 99.9°°C	0.1 K	+/- 0.1 K +/- 1 digit
Combination Chloride Electrode	10° to 100°C	Chlorides (ppm)	1.8 to 35,500 ppm	1 ppm	+/- 2% of measured value

Instrument Name	Operational Limit(s)	Variable Measured	Measurement Range	Resolution	Accuracy
Radiation Energy Balance Systems Q* Radiometer		Q* (mV)			Error range from +/-0% at 0 m/s to +/-5.9% at 7 m/s
Tipping Bucket Rain Gauge (TE525)	0° to +50°C	Precipitation (mm)		0.1mm	+/- 1.0% at precipitation rate of 5cm/hour or less

APPENDIX D: DATA LOGGER PROGRAM

```
Final Storage Label File for:  POD03MET.CSI
Date:  5/7/2003
Time:  15:57:28

166 Output_Table  30.00 Min
1 166 L
2 Day_RTM  L
3 Hour_Minute_RTM  L
4 battery_AVG  L
5 int_temp_AVG  L
6 Qgplate  L
7 Tair  L
8 Temp5cm  L
9 Qstar_wm2_AVG  L
10 floatpot  L
11 rain_TOT  L
12 Ct  L
13 Temp_degC  L
14 TDR1_mc_AVG  L
15 TDR2_mc_AVG  L
16 C25mScm1  L
```

Estimated Total Final Storage Locations used per day 768.0

```
POD03MET.CSI
;{CR10X}
;NB Pok Site 2003
;setup to monitor net radiation, ground temp, soil moisture etc
;program: Mike Shantz 2003

*Table 1 Program
  01: 10          Execution Interval (seconds)

1:  Batt Voltage (P10)
 1: 1           Loc [ battery   ]

2:  Internal Temperature (P17)
 1: 2           Loc [ int_temp  ]

3:  Volt (SE) (P1)
 1: 1           Reps
 2: 3           25 mV Slow Range
 3: 1           SE Channel
 4: 3           Loc [ Qgplate   ]
 5: 36.4        Mult
 6: 0.0         Offset

4:  Thermocouple Temp (DIFF) (P14)
 1: 2           Reps
 2: 1           2.5 mV Slow Range
 3: 2           DIFF Channel
 4: 1           Type T (Copper-Constantan)
 5: 2           Ref Temp (Deg. C) Loc [ int_temp  ]
 6: 4           Loc [ Tair      ]
 7: 1.0         Mult
 8: 0.0         Offset

5:  Excite-Delay (SE) (P4)
 1: 1           Reps
 2: 5           2500 mV Slow Range
 3: 7           SE Channel
 4: 3           Excite all reps w/Exchan 3
 5: 60          Delay (units 0.01 sec)
 6: 2500        mV Excitation
 7: 8           Loc [ floatpot  ]
 8: 0.9146      Mult
 9: 0.0         Offset

6:  Pulse (P3)
 1: 1           Reps
 2: 8           Control Port 8
 3: 2           Switch Closure, All Counts
 4: 9           Loc [ rain      ]
 5: 0.1         Mult
 6: 0.0         Offset
```

```
; Sampling of CS547A Conductivity and Temperature
; probe and A547 Interface

7:  Full Bridge (P6)
 1: 1          Reps
 2: 15         2500 mV Fast Range
 3: 5          DIFF Channel
 4: 1          Excite all reps w/Exchan 1
 5: 2500       mV Excitation
 6: 10         Loc [ Rs        ]
 7: -.001      Mult
 8: 1          Offset

8:  BR Transform Rf[X/(1-X)] (P59)
 1: 1          Reps
 2: 10         Loc [ Rs        ]
 3: 1          Multiplier (Rf)

9:  CASE (P93)
 1: 10         Case Loc [ Rs        ]

10:  If Case Location < F (P83)
 1: 1.8        F
 2: 30         Then Do

11:  AC Half Bridge (P5)
 1: 1          Reps
 2: 15         2500 mV Fast Range
 3: 10         SE Channel
 4: 1          Excite all reps w/Exchan 1
 5: 2500       mV Excitation
 6: 10         Loc [ Rs        ]
 7: 1.0        Mult
 8: 0.0        Offset

12:  BR Transform Rf[X/(1-X)] (P59)
 1: 1          Reps
 2: 10         Loc [ Rs        ]
 3: 1          Multiplier (Rf)

13:  End (P95)

14:  If Case Location < F (P83)
 1: 9.25       F
 2: 30         Then Do

15:  Full Bridge (P6)
 1: 1          Reps
 2: 15         2500 mV Fast Range
 3: 5          DIFF Channel
 4: 1          Excite all reps w/Exchan 1
 5: 2500       mV Excitation
 6: 10         Loc [ Rs        ]
 7: -.001      Mult
 8: 1          Offset

16:  BR Transform Rf[X/(1-X)] (P59)
 1: 1          Reps
 2: 10         Loc [ Rs        ]
 3: 1          Multiplier (Rf)
```

```
17:  End (P95)

18:  If Case Location < F (P83)
 1: 280      F
 2: 30       Then Do

19:  Full Bridge (P6)
 1: 1        Reps
 2: 14       250 mV Fast Range
 3: 5        DIFF Channel
 4: 1        Excite all reps w/Exchan 1
 5: 2500     mV Excitation
 6: 10       Loc [ Rs         ]
 7: -.001    Mult
 8: 1        Offset

20:  BR Transform Rf[X/(1-X)] (P59)
 1: 1        Reps
 2: 10       Loc [ Rs         ]
 3: 1        Multiplier (Rf)

21:  End (P95)

22:  End (P95)

23:  Z=F (P30)
 1: 20       F
 2: 00       Exponent of 10
 3: 11       Z Loc [ Rp         ]

24:  Z=X*F (P37)
 1: 11       X Loc [ Rp         ]
 2: .00032   F
 3: 11       Z Loc [ Rp         ]

25:  Z=X*F (P37)
 1: 11       X Loc [ Rp         ]
 2: -.1      F
 3: 11       Z Loc [ Rp         ]

26:  Z=X+F (P34)
 1: 11       X Loc [ Rp         ]
 2: -.005    F
 3: 11       Z Loc [ Rp         ]

27:  Z=X+Y (P33)
 1: 10       X Loc [ Rs         ]
 2: 11       Y Loc [ Rp         ]
 3: 10       Z Loc [ Rs         ]

28:  Z=1/X (P42)
 1: 10       X Loc [ Rs         ]
 2: 12       Z Loc [ oneoverRs  ]

29:  Z=X*F (P37)
 1: 12       X Loc [ oneoverRs  ]
 2: 1.378    F
 3: 13       Z Loc [ Ct         ]
```

```
; Measure Temperature

30:  Temp (107) (P11)
 1: 1         Reps
 2: 8         SE Channel
 3: 2         Excite all reps w/E2
 4: 14        Loc [ Temp_degC ]
 5: 1         Mult
 6: 0.0       Offset

; Correct EC for ionization

31:  If (X<=>F) (P89)
 1: 13        X Loc [ Ct        ]
 2: 4         <
 3: .474      F
 4: 30        Then Do

32:  Z=X*F (P37)
 1: 13        X Loc [ Ct        ]
 2: .95031    F
 3: 13        Z Loc [ Ct        ]

33:  Z=X+F (P34)
 1: 13        X Loc [ Ct        ]
 2: -.00378   F
 3: 13        Z Loc [ Ct        ]

34:  Else (P94)

35:  Polynomial (P55)
 1: 1         Reps
 2: 13        X Loc [ Ct        ]
 3: 13        F(X) Loc [ Ct        ]
 4: -.02889   C0
 5: .98614    C1
 6: .02846    C2
 7: 0.0       C3
 8: 0.0       C4
 9: 0.0       C5

36:  End (P95)

; Correct EC for Temperature

37:  Z=X+F (P34)
 1: 14        X Loc [ Temp_degC ]
 2: -25       F
 3: 15        Z Loc [ A         ]

38:  Z=X*F (P37)
 1: 13        X Loc [ Ct        ]
 2: 100       F
 3: 16        Z Loc [ Ct100     ]

39:  Z=X*F (P37)
 1: 15        X Loc [ A         ]
 2: 2         F
 3: 17        Z Loc [ TCProces  ]
```

```
40:  Z=X+F (P34)
 1: 17       X Loc [ TCProces  ]
 2: 100      F
 3: 17       Z Loc [ TCProces  ]

41:  Z=X/Y (P38)
 1: 16       X Loc [ Ct100     ]
 2: 17       Y Loc [ TCProces  ]
 3: 18       Z Loc [ C25mScm1  ]

;
;measure TDR
;

42:  If time is (P92)
 1: 0000     Minutes (Seconds --) into a
 2: 30       Interval (same units as above)
 3: 30       Then Do

43:  Do (P86)
 1: 41       Set Port 1 High

44:  Beginning of Loop (P87)
 1: 1        Delay
 2: 2        Loop Count

45:  End (P95)

46:  Pulse (P3)
 1: 1        Reps
 2: 1        Pulse Channel 1
 3: 21       Low Level AC, Output Hz
 4: 19       Loc [ TDR1_khz  ]
 5: 0.001    Mult
 6: 0.0      Offset

47:  Do (P86)
 1: 51       Set Port 1 Low

48:  Z=1/X (P42)
 1: 19       X Loc [ TDR1_khz  ]
 2: 20       Z Loc [ TDR1_per  ]

49:  Polynomial (P55)
 1: 1        Reps
 2: 20       X Loc [ TDR1_per  ]
 3: 21       F(X) Loc [ TDR1_mc   ]
 4: -.187    C0
 5: 0.037    C1
 6: 0.335    C2
 7: 0.0      C3
 8: 0.0      C4
 9: 0.0      C5

50:  End (P95)

51:  If time is (P92)
 1: 0000     Minutes (Seconds --) into a
 2: 30       Interval (same units as above)
 3: 30       Then Do
```

```
52:  Do (P86)
 1: 42        Set Port 2 High

53:  Beginning of Loop (P87)
 1: 1         Delay
 2: 2         Loop Count

54:  End (P95)

55:  Pulse (P3)
 1: 1         Reps
 2: 2         Pulse Channel 2
 3: 21        Low Level AC, Output Hz
 4: 22        Loc [ TDR2_Khz  ]
 5: 0.001     Mult
 6: 0.0       Offset

56:  Do (P86)
 1: 52        Set Port 2 Low

57:  Z=1/X (P42)
 1: 22        X Loc [ TDR2_Khz  ]
 2: 23        Z Loc [ TDR2_per  ]

58:  Polynomial (P55)
 1: 1         Reps
 2: 23        X Loc [ TDR2_per  ]
 3: 24        F(X) Loc [ TDR2_mc   ]
 4: -.187     C0
 5: 0.037     C1
 6: 0.335     C2
 7: 0.0       C3
 8: 0.0       C4
 9: 0.0       C5

59:  End (P95)

60:  Volt (Diff) (P2)
 1: 1         Reps
 2: 4         250 mV Slow Range
 3: 6         DIFF Channel
 4: 6         Loc [ Qstar_mV  ]
 5: 1.0       Mult
 6: 0.0       Offset

61:  If (X<=>F) (P89)
 1: 6         X Loc [ Qstar_mV  ]
 2: 3         >=
 3: 0.0       F
 4: 30        Then Do

62:  Z=X*F (P37)
 1: 6         X Loc [ Qstar_mV  ]
 2: 9.09      F
 3: 7         Z Loc [ Qstar_Wm2 ]

63:  Else (P94)
```

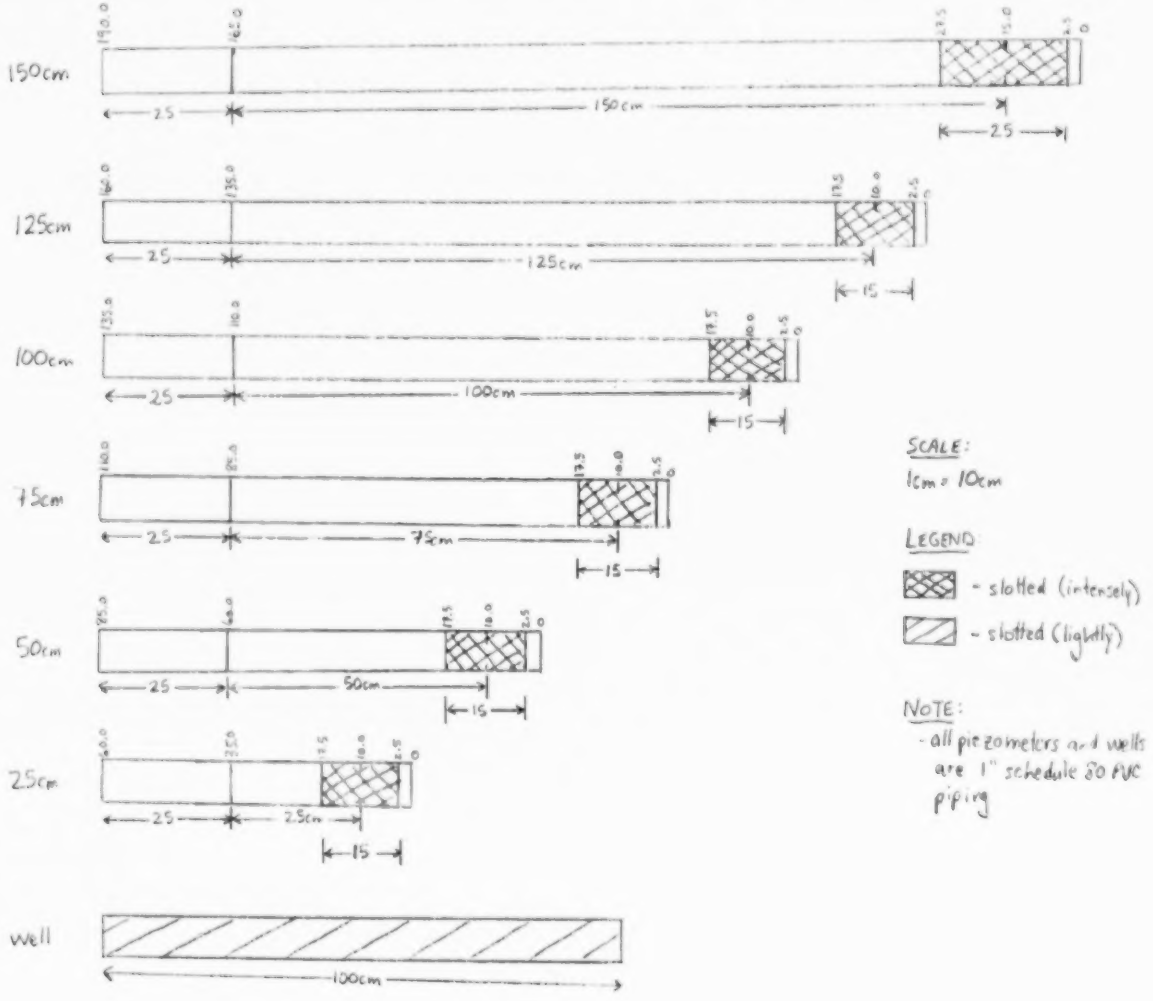
```
64:  Z=X*F (P37)
 1: 6          X Loc [ Qstar_mV  ]
 2: 11.51      F
 3: 7          Z Loc [ Qstar_Wm2 ]

65:  End (P95)

66:  If time is (P92)
 1: 0000       Minutes (Seconds --) into a
 2: 30         Interval (same units as above)
 3: 10         Set Output Flag High (Flag 0)

67:  Real Time (P77)
 1: 110        Day,Hour/Minute (midnight = 0000)

68:  Average (P71)
 1: 2          Reps
 2: 1          Loc [ battery   ]

69:  Sample (P70)
 1: 3          Reps
 2: 3          Loc [ Qgplate   ]

70:  Average (P71)
 1: 1          Reps
 2: 7          Loc [ Qstar_Wm2 ]

71:  Sample (P70)
 1: 1          Reps
 2: 8          Loc [ floatpot  ]

72:  Totalize (P72)
 1: 1          Reps
 2: 9          Loc [ rain      ]

73:  Sample (P70)
 1: 1          Reps
 2: 13         Loc [ Ct        ]

74:  Sample (P70)
 1: 1          Reps
 2: 14         Loc [ Temp_degC ]

75:  Average (P71)
 1: 1          Reps
 2: 21         Loc [ TDR1_mc   ]

76:  Average (P71)
 1: 1          Reps
 2: 24         Loc [ TDR2_mc   ]

77:  Sample (P70)
 1: 1          Reps
 2: 18         Loc [ C25mScm1  ]

78:  Serial Out (P96)
 1: 71         SM192/SM716/CSM1
```

```
*Table 2 Program
  02: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines

End Program

-Input Locations-
1 battery    1 1 1
2 int_temp   1 2 1
3 Qgplate    1 1 1
4 Tair       5 1 1
5 Temp5cm    17 1 1
6 Qstar_mV   1 3 1
7 Qstar_Wm2  1 1 2
8 floatpot   1 1 1
9 rain       1 1 1
10 Rs         1 7 9
11 Rp         1 4 4
12 oneoverRs  1 1 1
13 Ct         1 6 4
14 Temp_degC  1 2 1
15 A          1 1 1
16 Ct100      1 1 1
17 TCProces   1 2 2
18 C25mScm1   1 1 1
19 TDR1_khz   1 1 1
20 TDR1_per   1 1 1
21 TDR1_mc    1 1 1
22 TDR2_Khz   1 1 1
23 TDR2_per   1 1 1
24 TDR2_mc    1 1 1
25 _________  0 0 0
26 _________  0 0 0
27 _________  0 0 0
28 _________  0 0 0
-Program Security-
0000
0000
0000
-Mode 4-
-Final Storage Area 2-
0
-CR10X ID-
0
-CR10X Power Up-
3
```

APPENDIX E: HYDRAULIC CONDUCTIVITY MEASUREMENT DATES

Nest -Piezometer	Date
n02 - well	Aug 4/03
n02 - deep	Jul 21/03
n02 - 150 cm	Jul 21/03
n02 - 125 cm	Aug 4/03
n02 - 100 cm	Aug 4/03
n02 - 75 cm	frozen
n02 - 50 cm	frozen
n03 - well	frozen
n03 - 150 cm	Jul 22/03
n03 - 125 cm	Jul 22/03
n03 - 100 cm	Jul 22/03
n03 - 75 cm	Jul 22/03
n03 - 50 cm	Jul 22/03
n04 - well	Aug 4/03
n04 - deep	not installed yet
n04 - 150 cm	Aug 4/03
n04 - 125 cm	Jul 21/03
n04 - 100 cm	Aug 4/03
n04 - 75 cm	Aug 4/03
n04 - 50 cm	Jul 21/03
n05 - well	frozen
n05 - 150 cm	Jul 22/03
n05 - 125 cm	Jul 22/03
n05 - 100 cm	Jul 22/03
n05 - 75 cm	dry
n05 - 50 cm	dry
n06 - well	Jul 22/03
n06 - 75 cm	Jul 22/03
n06 - 50 cm	Jul 22/03
n07 - well	frozen
n07 - deep	Jul 22/03
n07 - 100 cm	Jul 22/03
n07 - 75 cm	frozen
n07 - 50 cm	frozen
n08 - well	not done
n08 - 100 cm	Aug 6/03
n08 - 75 cm	Aug 6/03
n08 - 50 cm	Aug 6/03
n08 - 25 cm	Aug 6/03

APPENDIX F: PIEZOMETER AND WELL DIMENSIONS

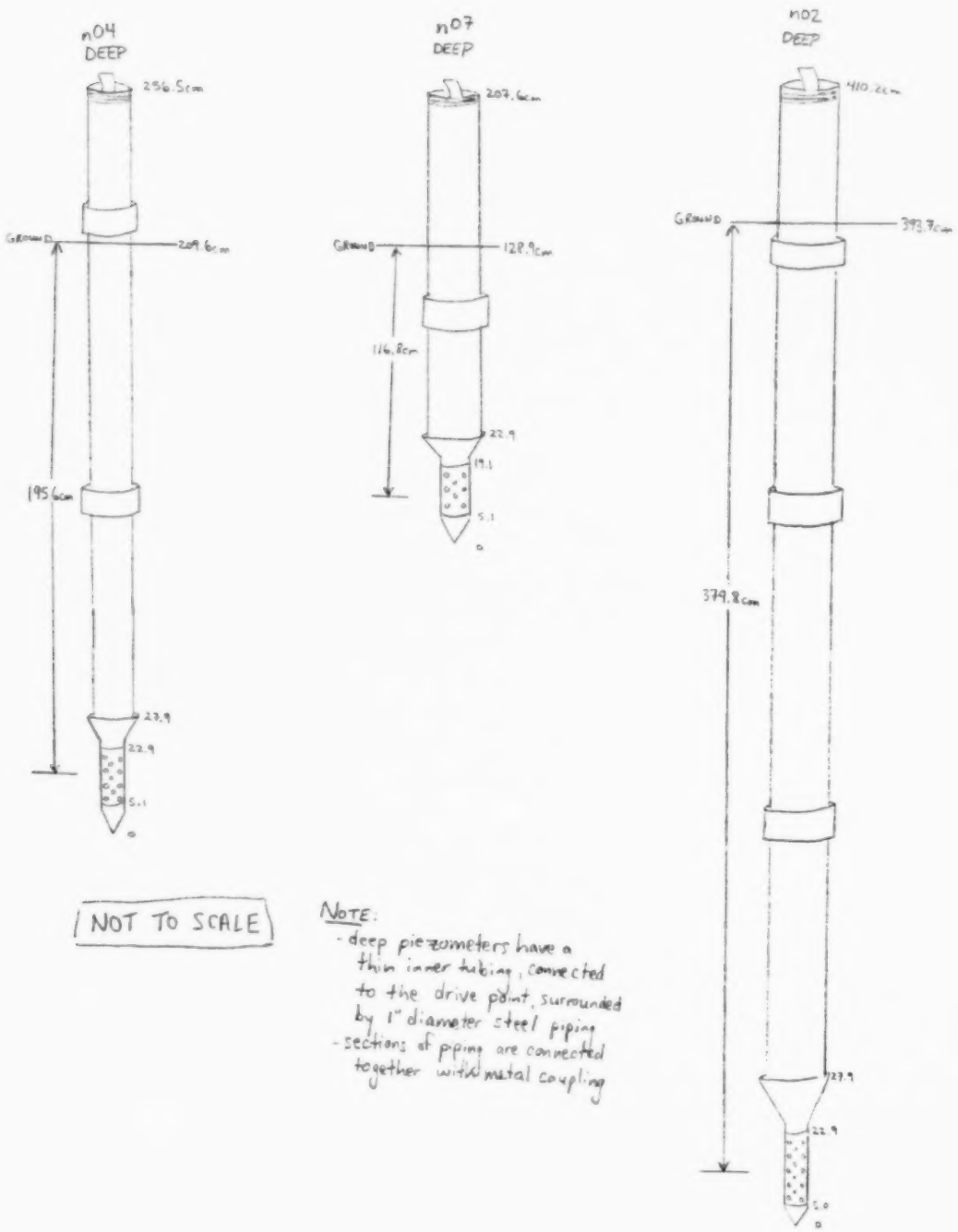


SCALE:
1cm = 10cm

LEGEND
- slotted (intensely)
- slotted (lightly)

NOTE:
- all piezometers and wells are 1" schedule 80 PVC piping

APPENDIX G: DEEP PIEZOMETER DIMENSIONS



NOT TO SCALE

NOTE:
- deep piezometers have a thin inner tubing, connected to the drive point, surrounded by 1" diameter steel piping
- sections of piping are connected together with metal coupling

APPENDIX H: PIEZOMETER INSTALLATION, DEFROST AND REPLACEMENT DATES (2003)

Nest	Depth	Installation Date	Date Defrosted	Replacement Date (if required)
n01	well (100 cm)	May-05	Jun-02	
	150 cm	May-05	May-05	
	125 cm	May-05	May-05	
	100 cm	May-05	May-05	
	75 cm	May-05	May-05	
	50 cm	May-05	May-05	
n02	well (100 cm)	May-05	Jul-29	
	deep (379.8 cm)	May-22	May-22	
	150 cm	May-05	Jul-10	11-Jul
	125 cm	May-05	Jul-29	27-Jul
	100 cm	May-05	Jul-29	27-Jul
	75 cm	May-05	Aug-11	
	50 cm	May-05	Jul-10	11-Jul
n03	well (100 cm)	May-05	Jul-29	29-Jul
	150 cm	May-05	Jul-10	11-Jul
	125 cm	May-05	May-05	
	100 cm	May-05	May-05	
	75 cm	May-05	Jul-14	
	50 cm	May-05	Jun-12	
n04	well (100 cm)	May-05	Jul-29	
	deep (195.6 cm)	Aug-11	Aug-11	
	150 cm	May-05	May-22	23-Jul
	125 cm	May-05	Jul-10	
	100 cm	May-05	Jul-29	23-Jul
	75 cm	May-05	Jul-29	23-Jul
	50 cm	May-05	Jul-10	11-Jul
n05	well (100 cm)	May-05	May-19	
	150 cm	May-05	May-19	
	125 cm	May-05	May-22	
	100 cm	May-05	May-22	
	75 cm	May-05	May-22	
	50 cm	May-05	May-22	
n06	well (100 cm)	May-06	Jun30	11-Jul
	75 cm	May-06	Jun17	11-Jul
	50 cm	May-06	Jun26	

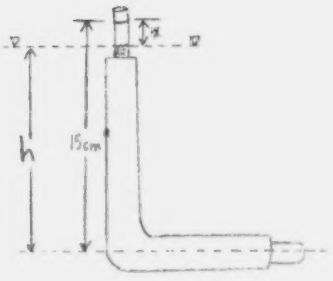
Nest	Depth	Installation Date	Date Defrosted	Replacement Date (if required)
n07	well (100 cm)	May-06	Aug-11	
	deep (116.8 cm)	May-22	May-22	
	100 cm	May-06	May-30	
	75 cm	May-06	Aug-11	
	50 cm	May-06	Jul-29	
n08	well (100 cm)	May-06	May-06	
	100 cm	May-06	May-06	
	75 cm	May-06	May-06	
	50 cm	May-06	May-06	
	25 cm	May-12	May-12	
n09	well (100 cm)	May-06	May-06	
	100 cm	May-06	May-06	
	75 cm	May-06	May-06	
	50 cm	May-06	May-06	
	25 cm	May-12	May-12	
n10	well (100 cm)	May-06	May-06	11-Jul
	100 cm	May-06	May-06	11-Jul
	75 cm	May-06	May-06	
	50 cm	May-06	May-06	
	25 cm	May-12	May-12	

APPENDIX I: CHLORIDE STANDARD CREATION METHOD

1. Ratio of NaCl to Cl:
    - 1.648 g NaCl = 1 g Cl
    - Ratio of NaCl to Cl = 58.5 / 35.5 = 1.648 (using molar weights)
2. Put 16.48 g of NaCl in graduated cylinder, filled to 100mL with deionized water – to create 100,000 ppm (100 g L^{-1}) standard
3. Took 10 mL of the 100,000 ppm standard, diluted to 100 mL (to get 10,000 ppm standard)
4. Continued process of dilution to get 1000, 100 and 10 ppm standards
5. Removed 30 mL of standard per day of testing, to avoid contamination of the original standards
6. Always measured 10 ppm first, then up to 100,000 ppm to minimize potential for contamination
7. Added 1 mL of ISA solution to each daily use standard

APPENDIX J: TENSIOMETER DIMENSIONS

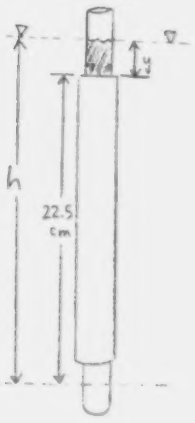
2cm, 5cm and 10cm:



$h = 15 - x$

x = measured length between line and water level (cm)

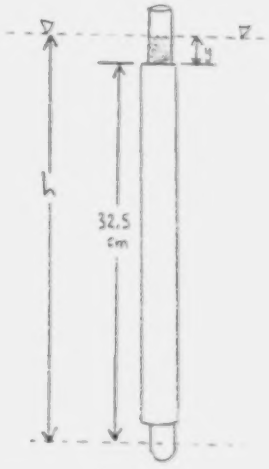
20cm:



$h = 22.5 + y$

y = measured length between gray casing and water level (cm)

30cm:



$h = 32.5 + y$

APPENDIX K: SALINITY RELATIONSHIP WITH CHLORIDES AND ELECTRICAL CONDUCTIVITY